Lecture Presentation

Nuclear Magnetic Resonance Logging

Advanced Multi-Well Formation Evaluation
Lecture Notes

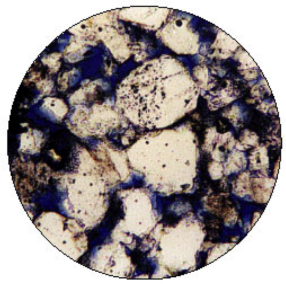
Fundamentals of Nuclear Magnetic Resonance Borehole Logging

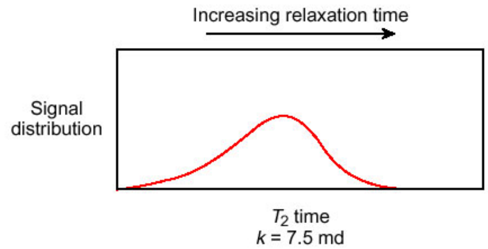
Carlos Torres-Verdín, Ph.D.
Professor
Department of Petroleum and Geosystems Engineering
The University of Texas at Austin

Objectives:

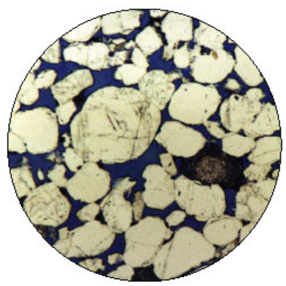
1. To introduce the basic physical and operational principles of NMR borehole logging,
2. To learn how to interpret NMR measurements made on rocks in terms of petrophysical properties,
3. To understand the advantages and limitations of NMR borehole logging with respect to conventional borehole logging measurements, and
4. To learn how to combine NMR measurements with rock-core data and standard borehole logs.

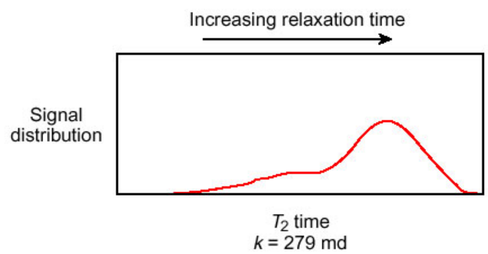
WILL THE WELL PRODUCE?





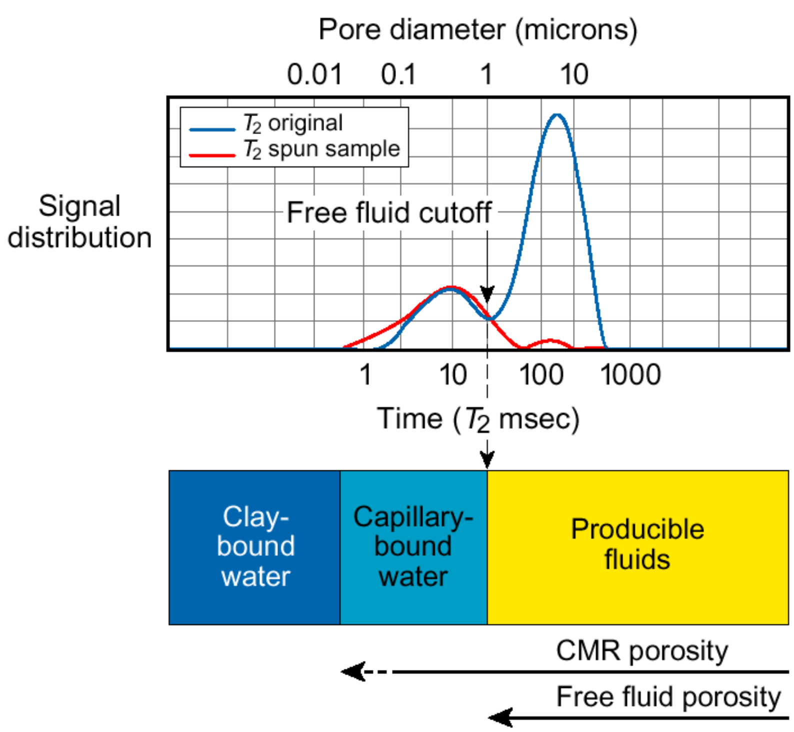
Porosity = 20%
Permeability = 7.5 md





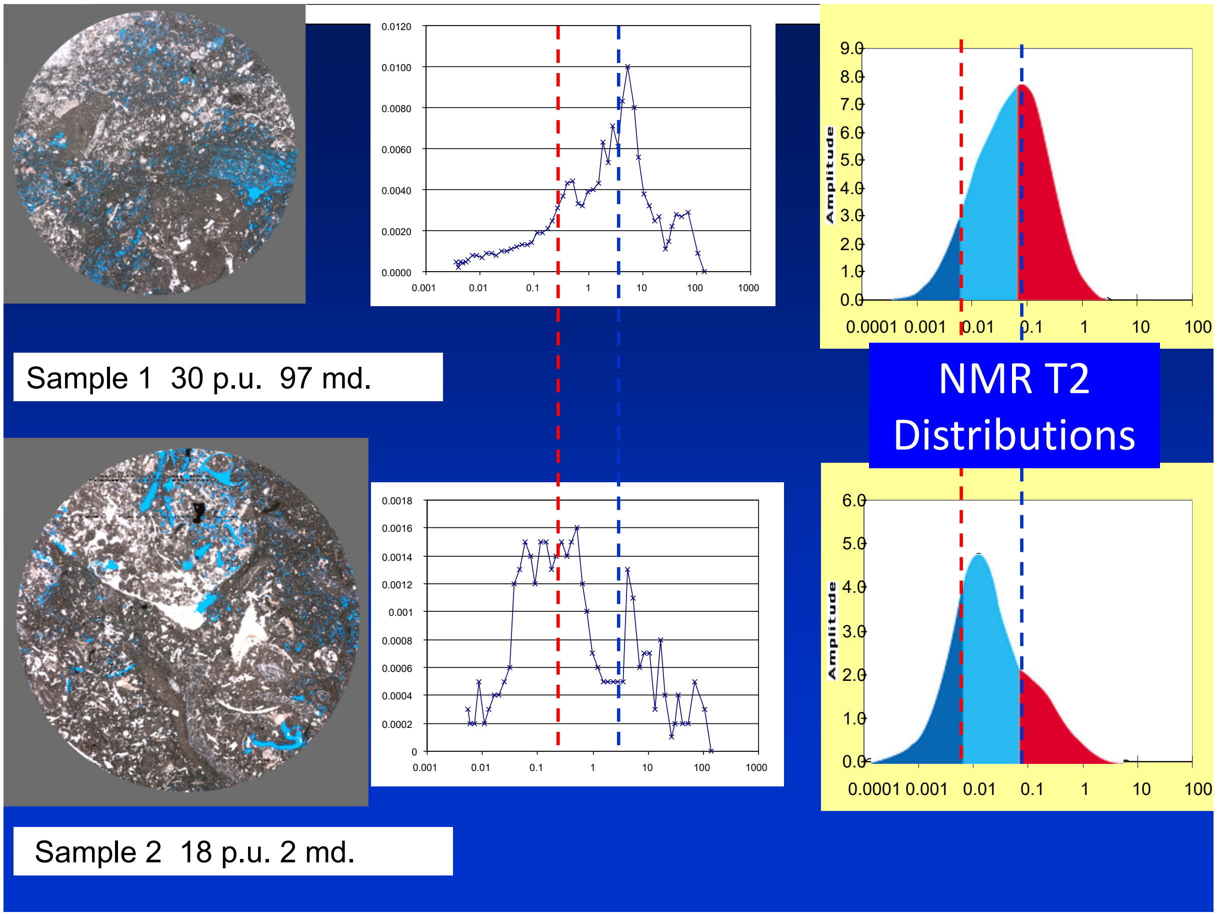
Porosity = 19.5%
Permeability = 279 md

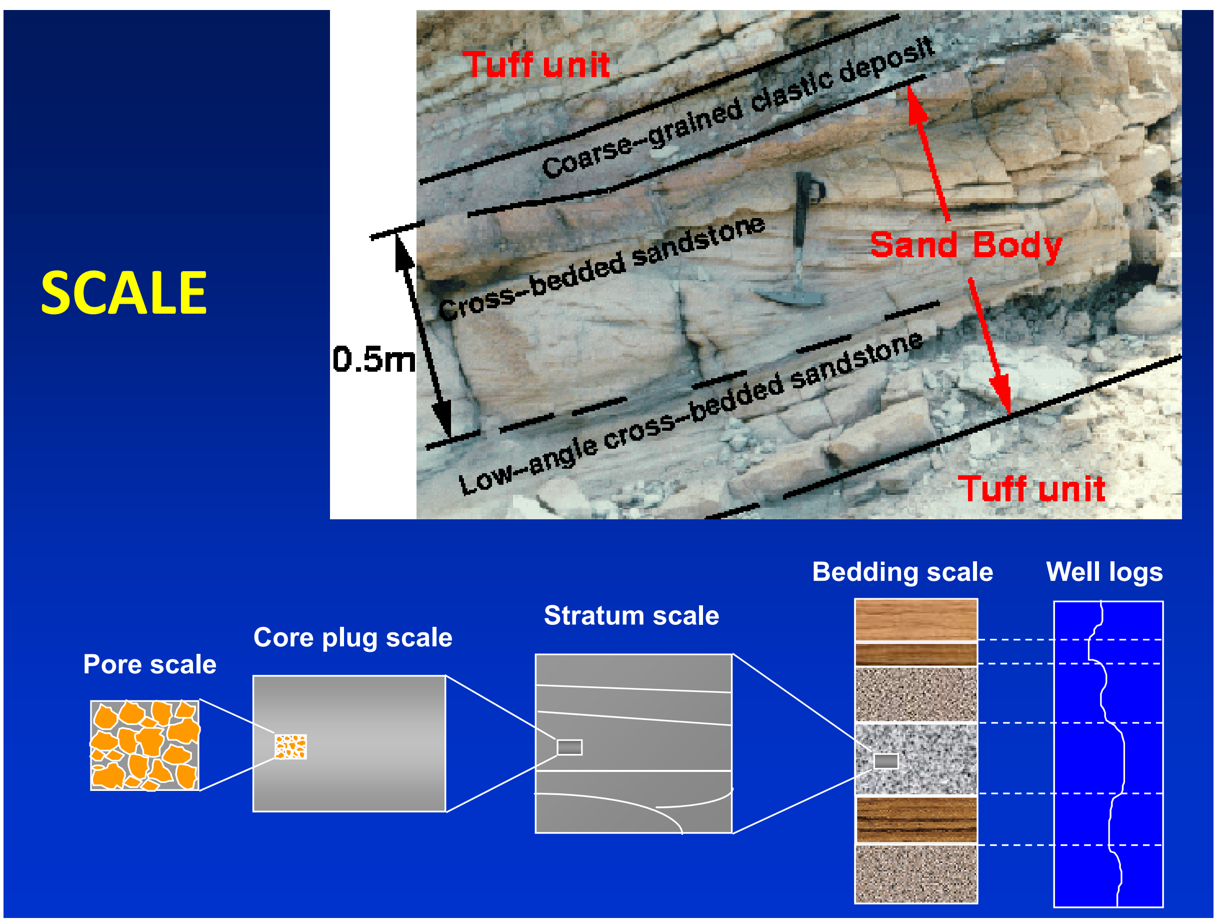
FREE FLUID vs. IRREDUCIBLE FLUID

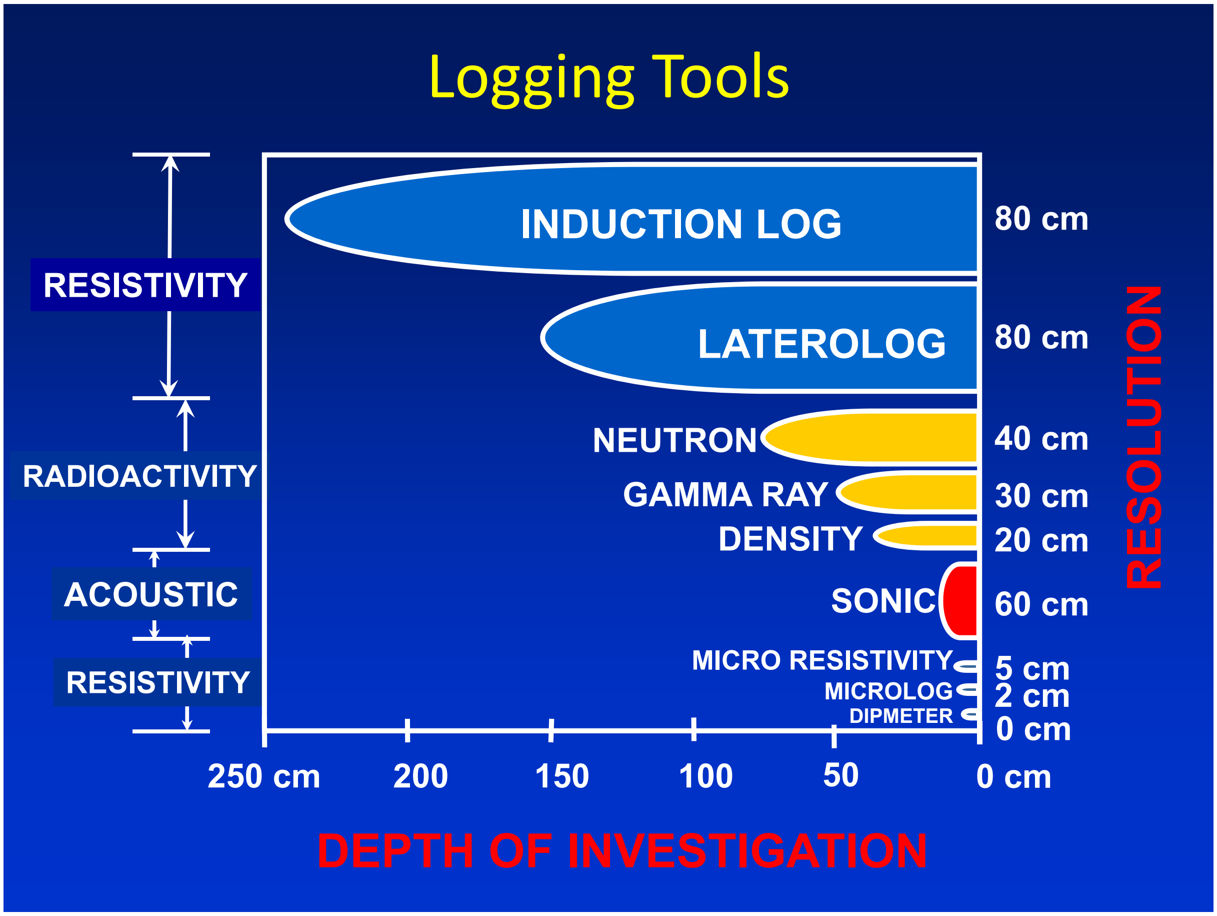


High Permeability Grainstone

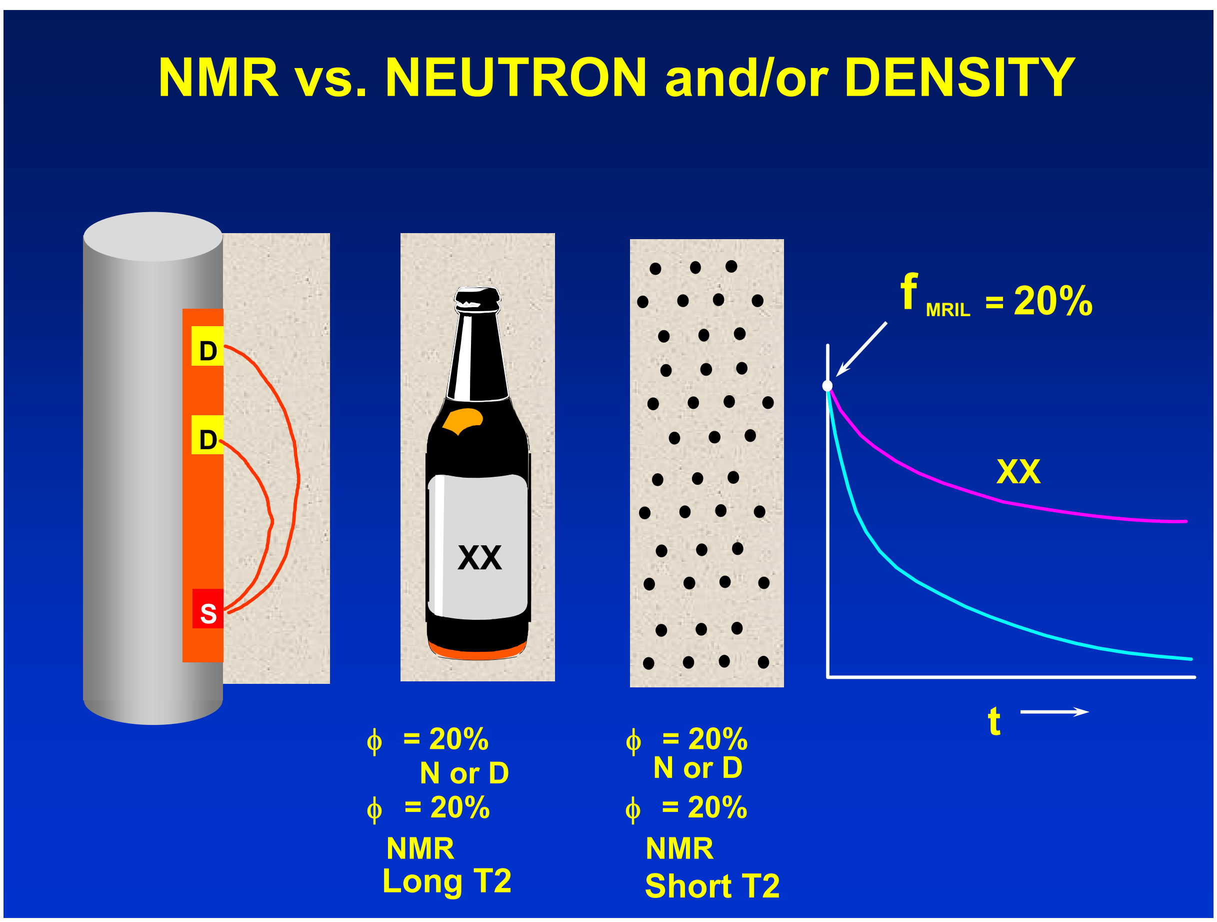
Low Permeability Wackestone


Sample 1 30 p.u. 97 md.
Sample 2 18 p.u. 2 md.
NMR T2
Distributions
Amplitude
0.0001 0.001 0.01 0.1 1 10 100
0.001 0.01 0.1 1 10 100 1000


SCALE
Tuff unit
Coarse-grained clastic deposit
Cross-bedded sandstone
Sand Body
0.5m
Low-angle cross-bedded sandstone
Tuff unit
Pore scale
Core plug scale
Stratum scale
Bedding scale
Well logs

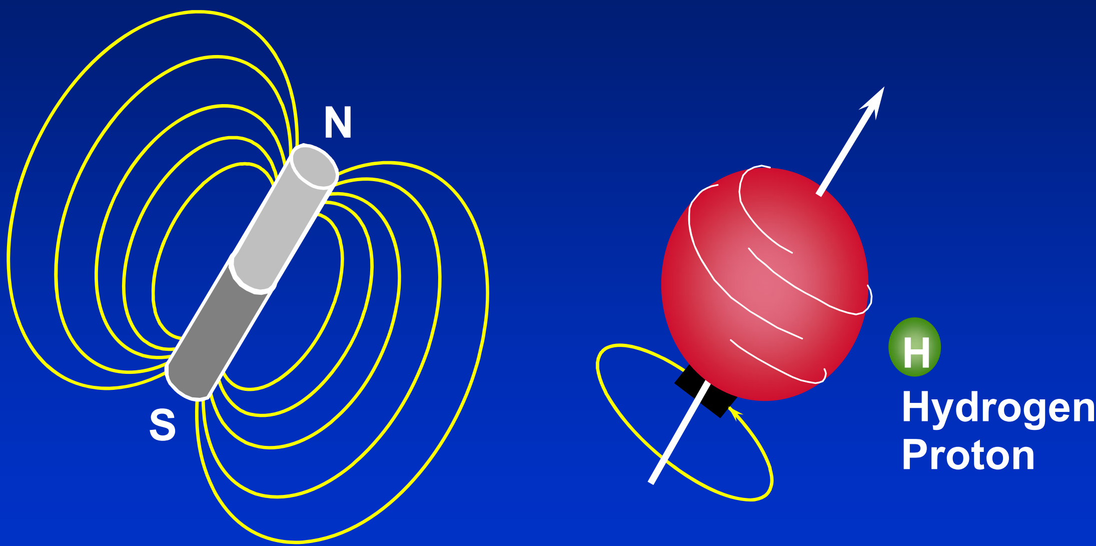


Logging Tools
RESISTIVITY
RADIOACTIVITY
ACOUSTIC
RESISTIVITY
INDUCTION LOG
LATEROLOG
NEUTRON
GAMMA RAY
DENSITY
SONIC
MICRO RESISTIVITY
MICROLOG
DIPMETER
80 cm
80 cm
40 cm
30 cm
20 cm
60 cm
5 cm
2 cm
0 cm
RESOLUTION
250 cm
200
150
100
50
0 cm
DEPTH OF INVESTIGATION

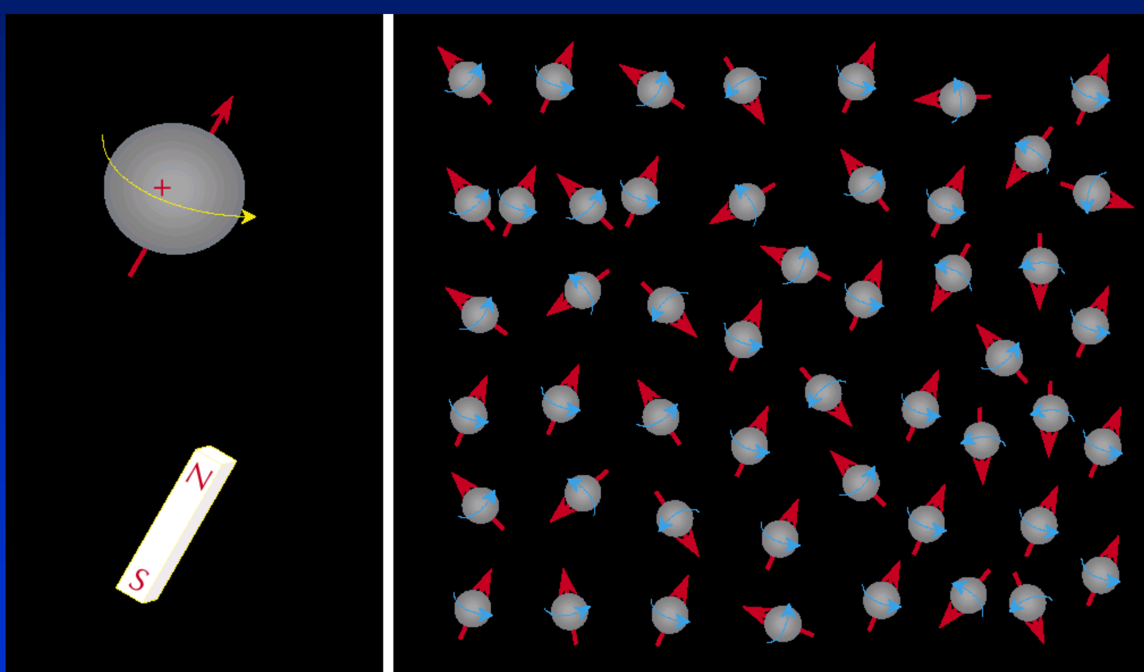


NMR vs. NEUTRON and/or DENSITY
D
D
S
XX
f MRIL = 20%
XX
t
ϕ = 20%
N or D
ϕ = 20%
NMR
Long T2
ϕ = 20%
N or D
ϕ = 20%
NMR
Short T2

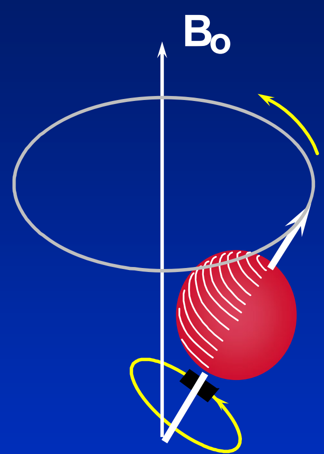
SPIN MAGNETIZATION

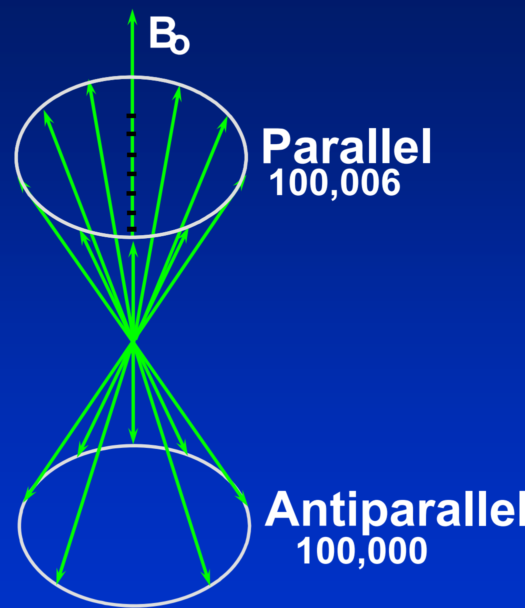


SPIN MAGNETIZATION



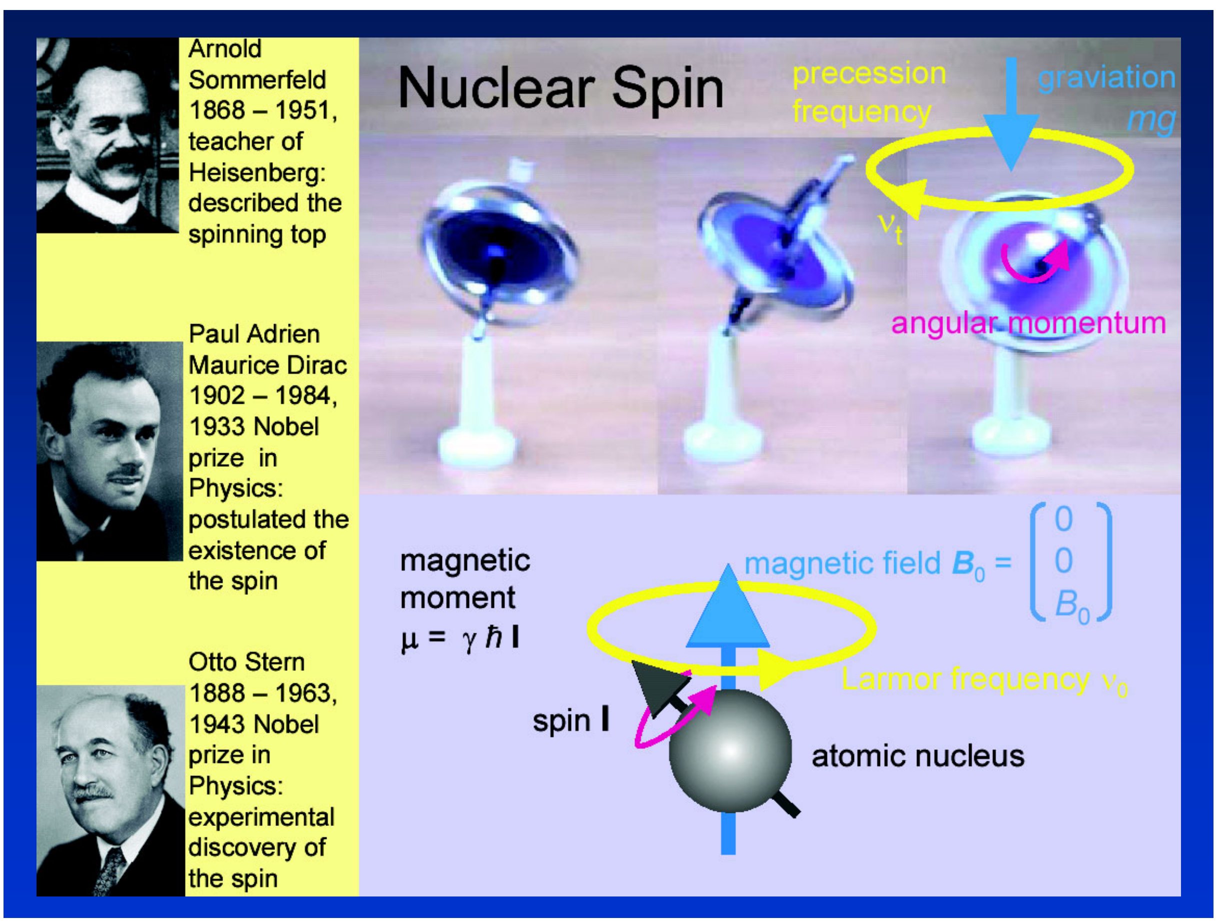
PRECESSION





Larmor Precession

freq. = $4258 \frac{Hz}{Gauss} \cdot B_o$

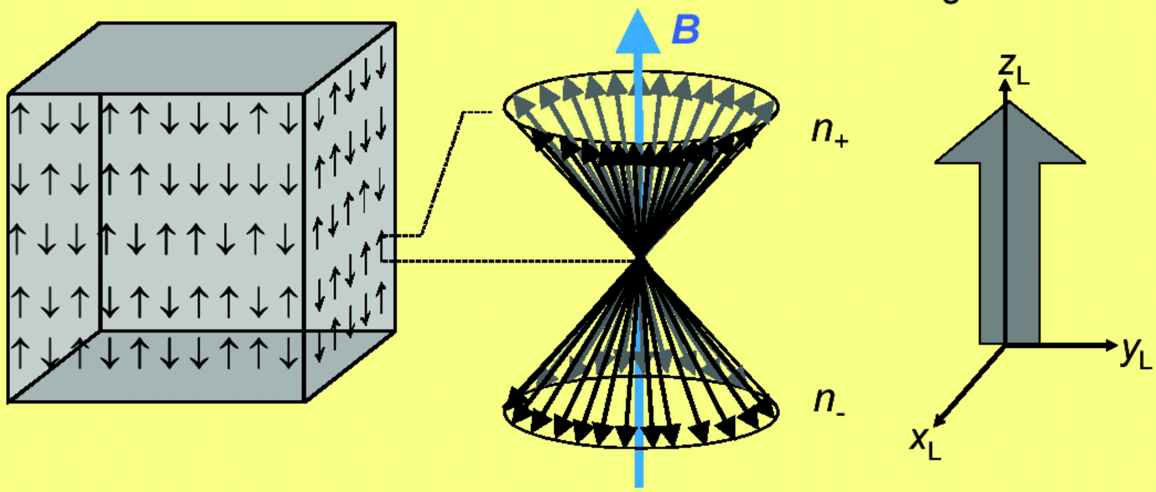


Macroscopic Magnetization

macroscopic sample:
10^{23} nuclear spins

$n_-/n_+ = \exp\{-\Delta E/k_B T\}$

vector sum:
macroscopic
magnetization ***M***



100 000 000 000 000 000 000 000 proton spins in a drop of water

LARMOR FREQUENCY

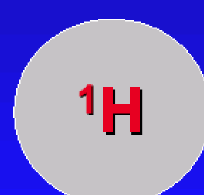
. . . the frequency at which the nuclear spin precess about the external static magnetic field

$$\nu_0 = \frac{\gamma}{2 \cdot \pi} \cdot B$$

γ gyromagnetic ratio

B static magnetic field

Nucleus	$\gamma/2\pi$ MHz/Tesla
^{1}H	42.58
^{13}C	10.7
^{23}Na	11.26



ELEMENTAL NMR RESPONSE

Nucleus [most common applications in log & core analysis]	$\gamma / 2\pi$ (Hz/Gauss)	I	Natural abundance (%)	Relative sensitivity
^{1}H [core and log]	4257.59	1/2	99.99	1.000
^{2}H [aqueous phase]	653.57	1	0.015	0.0097
^{13}C [need high freq.]	1070.5	1/2	1.10	0.0159
^{19}F [nonwetting phase]	4005.5	1/2	100.00	0.833
^{23}Na [salinity]	11.26	3/2	100.00	0.0925

LARMOR FREQUENCY

Tuning the NMR tool to the resonant frequency maximizes the signal amplitude

Larmor frequency is proportional to

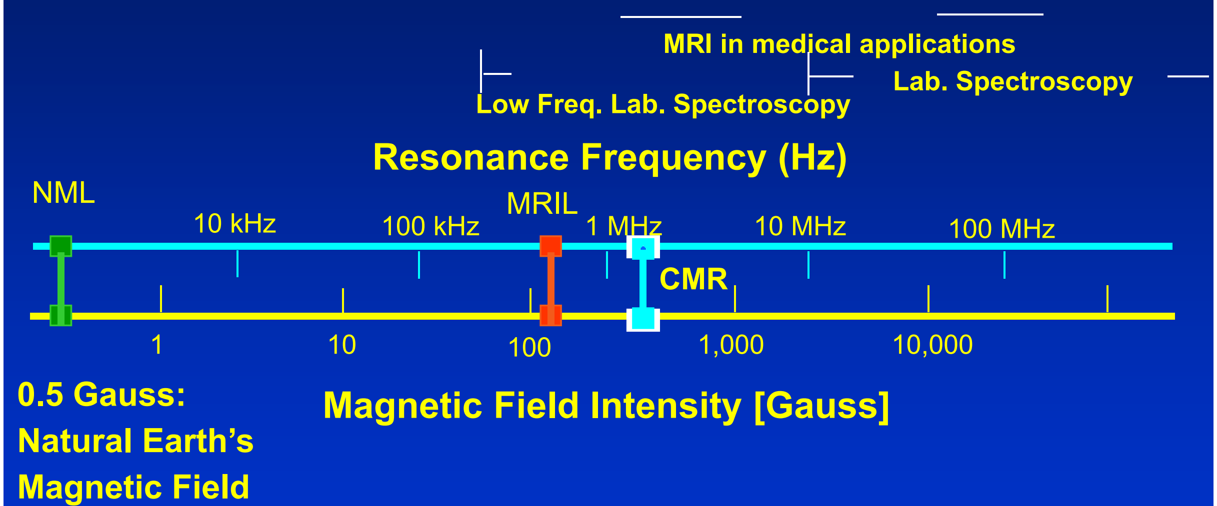
$$\nu_0 = \frac{\gamma}{2 \cdot \pi} \cdot B$$

- magnitude of the static magnetic field
- gyromagnetic ratio of the nucleus

different species can be differentiated/separated on the basis of frequencies

Strength is position dependend - local function

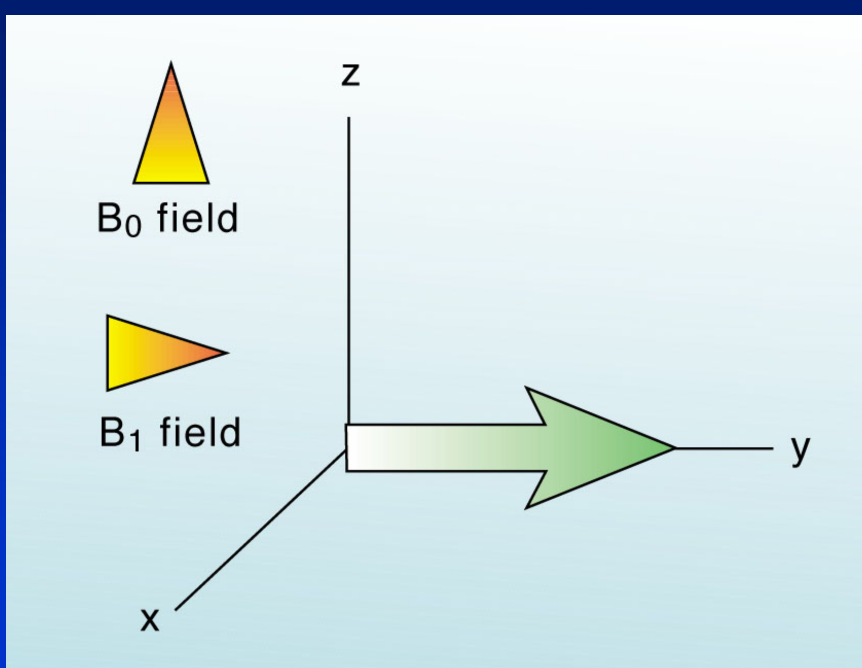
FREQUENCY- INTENSITY SPECTRUM



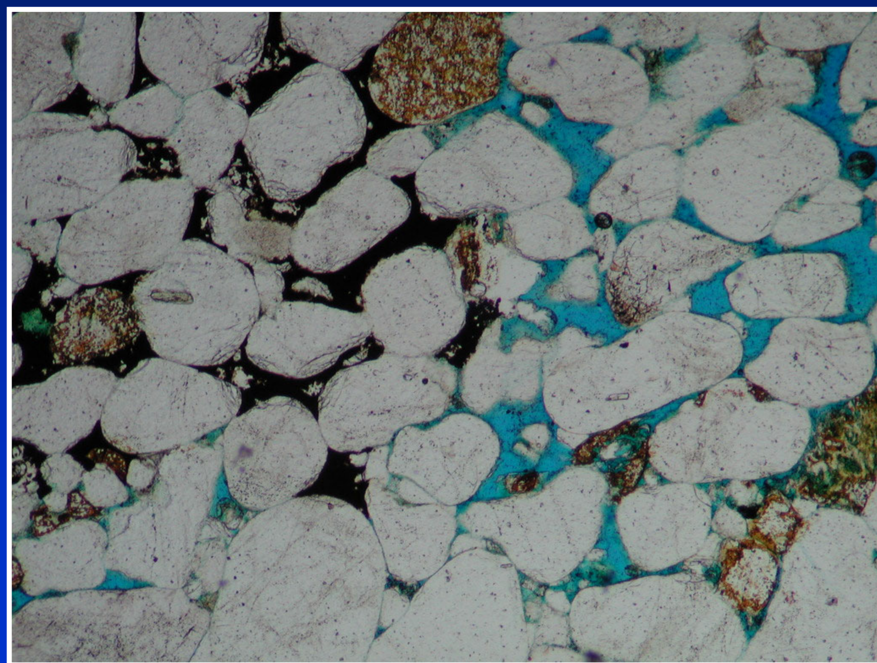
Larmor Frequency = γ B_0

γ $_{\text{Hydrogen}}$ = 4258 Hz

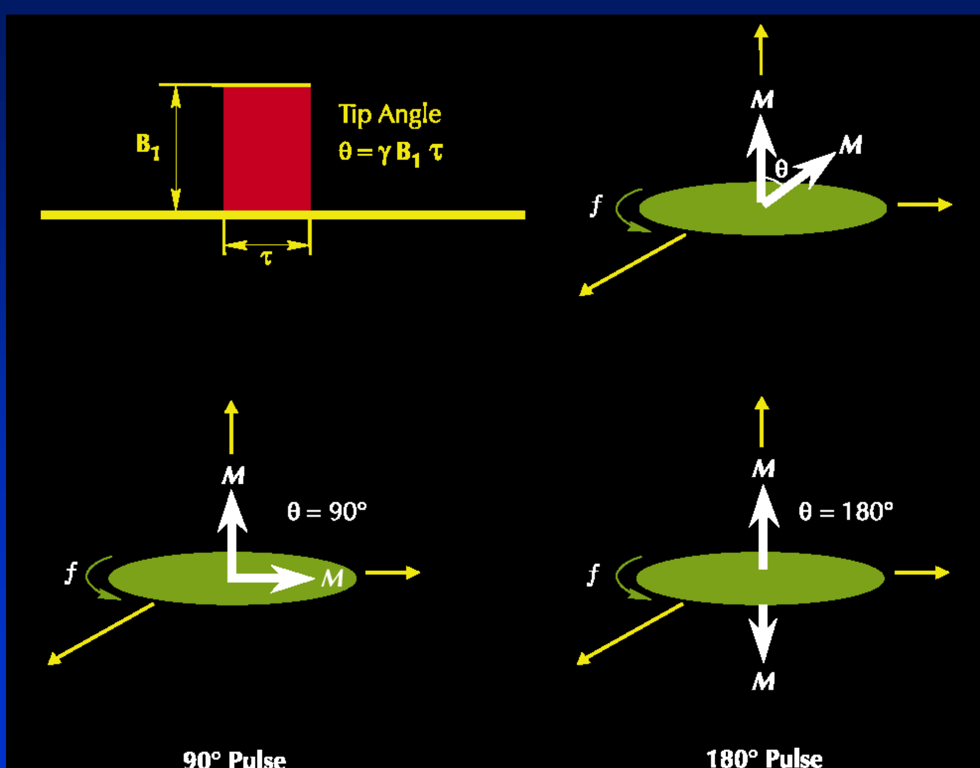
TRANSVERSAL TIPPING



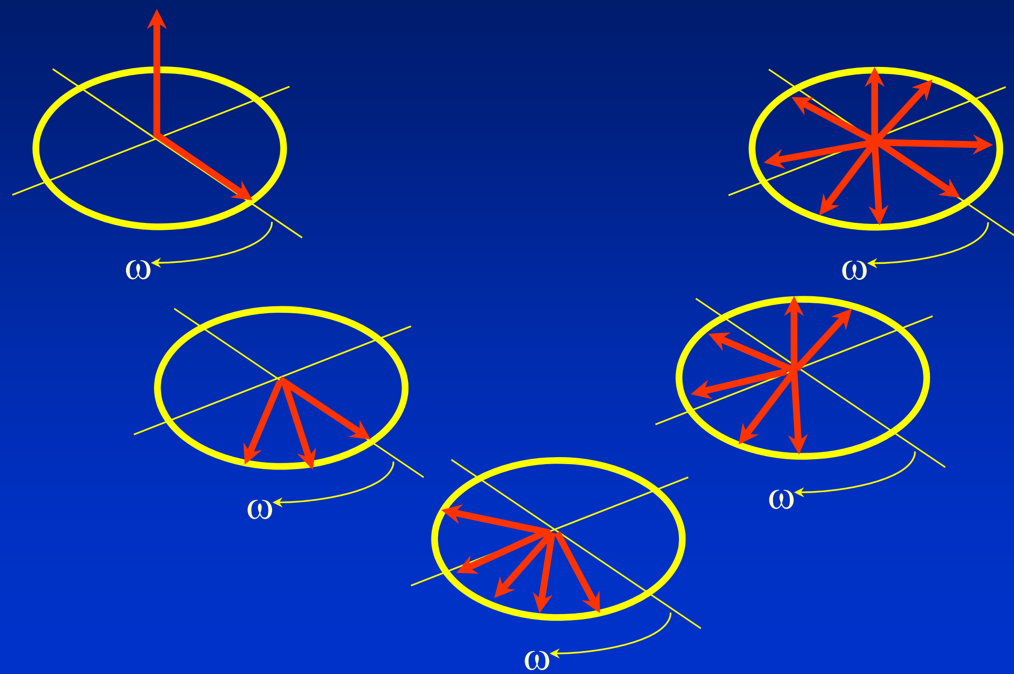
NMR Longitudinal Relaxation and Fluid Distribution in the Pore Space



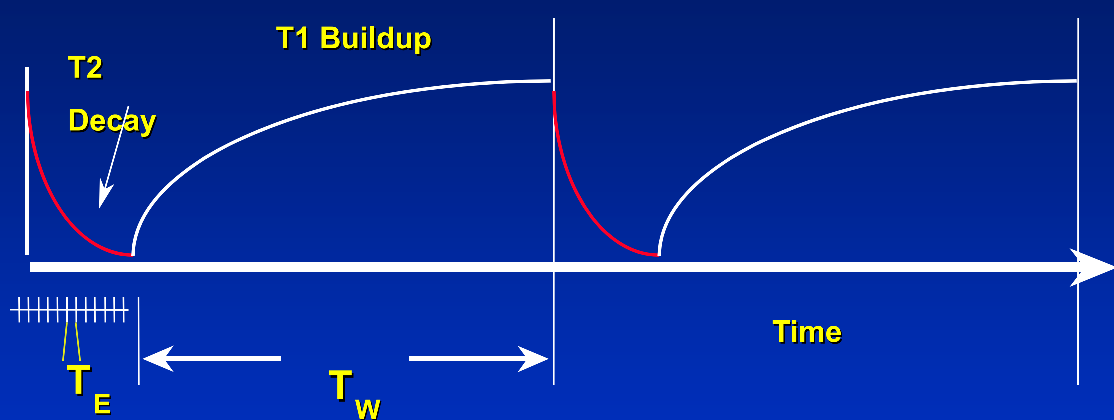
TRANSVERSAL TIPPING



TRANSVERSAL TIPPING and PROTON PRECESSION



LONGITUDINAL AND TRANSVERSE RELAXATION



- Two primary parameters that control NMR logging, TE and TW .

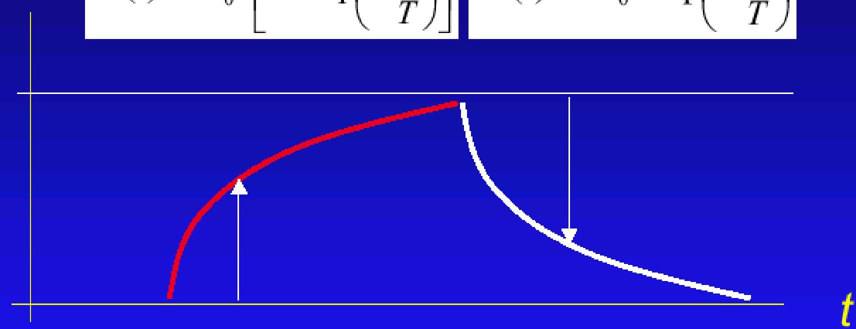
LONGITUDINAL AND TRANSVERSE RELAXATION

Polarization

$$M(t) = M_0 \cdot \left[1 - \exp\left(-\frac{t}{T}\right)\right]$$

Decay

$$M(t) = M_0 \cdot \exp\left(-\frac{t}{T}\right)$$



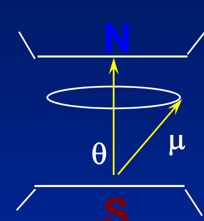
Two relaxation types → two relaxation times:

T_1 - longitudinal, or spin-lattice, relaxation time

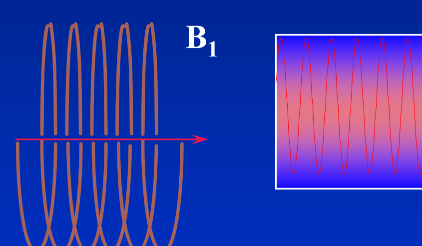
T_2 - transverse, or spin-spin, relaxation time

BASIC NMR INSTRUMENTATION COMPONENTS

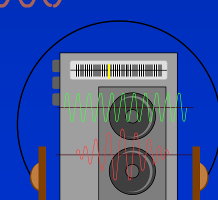
- **A time-constant magnetic field used to polarize the spins**

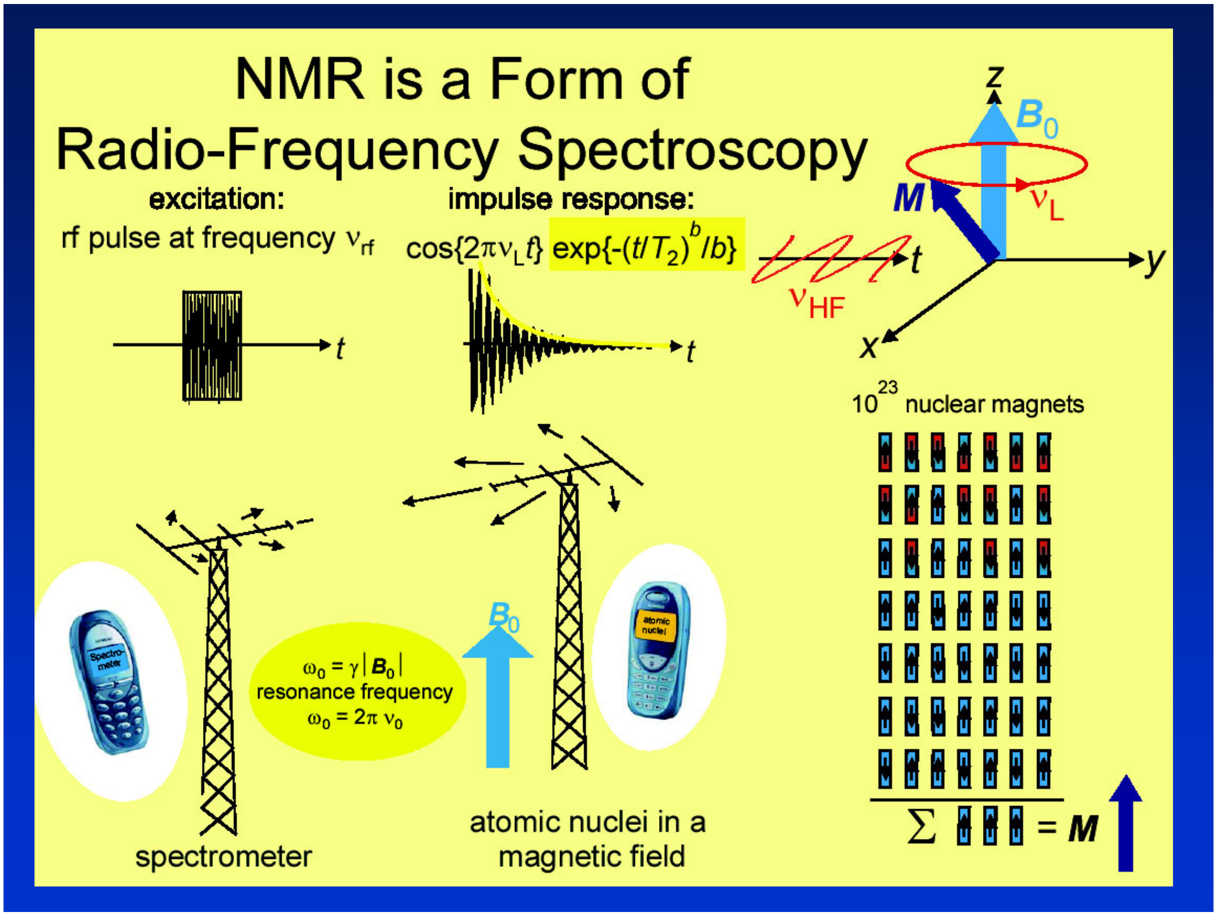


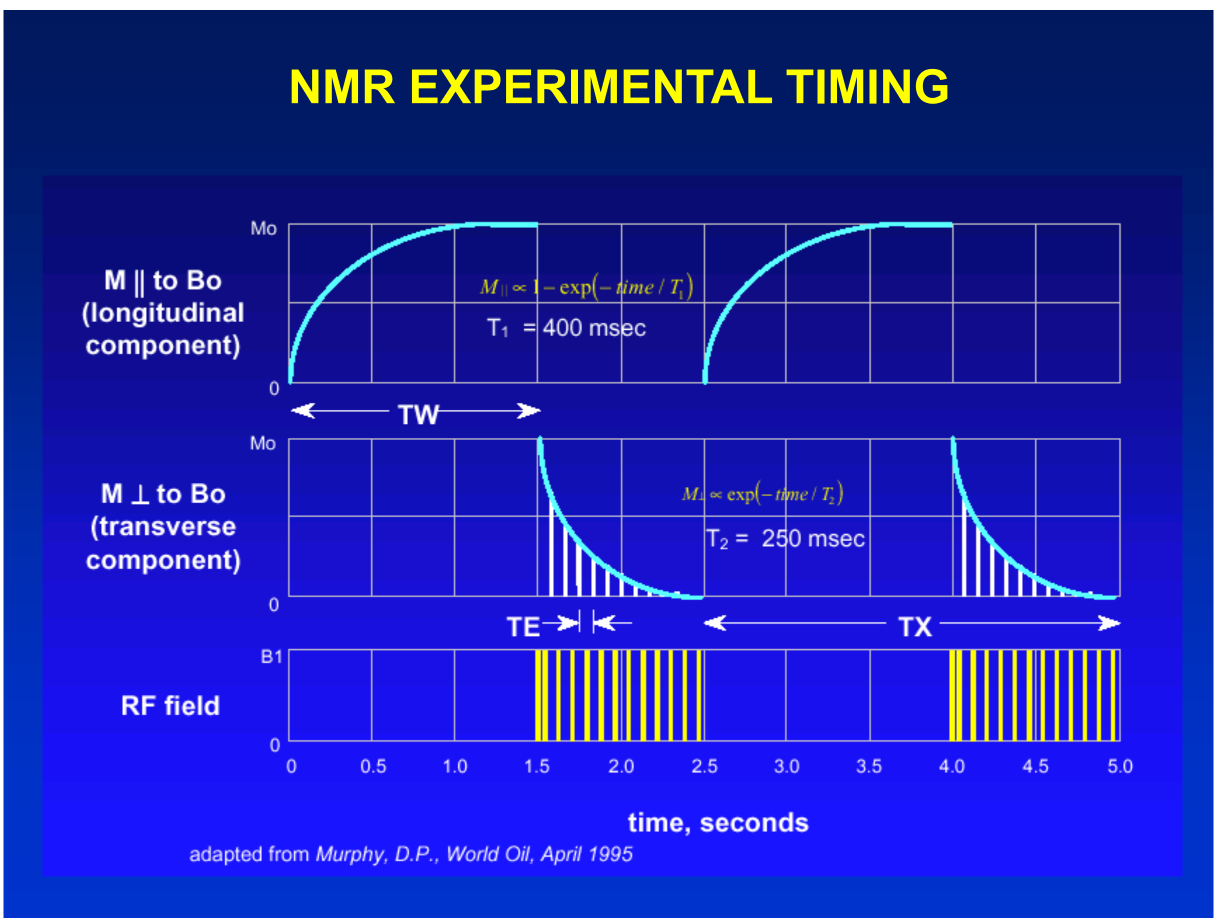
- **A time-varying RF magnetic field to excite the spins**



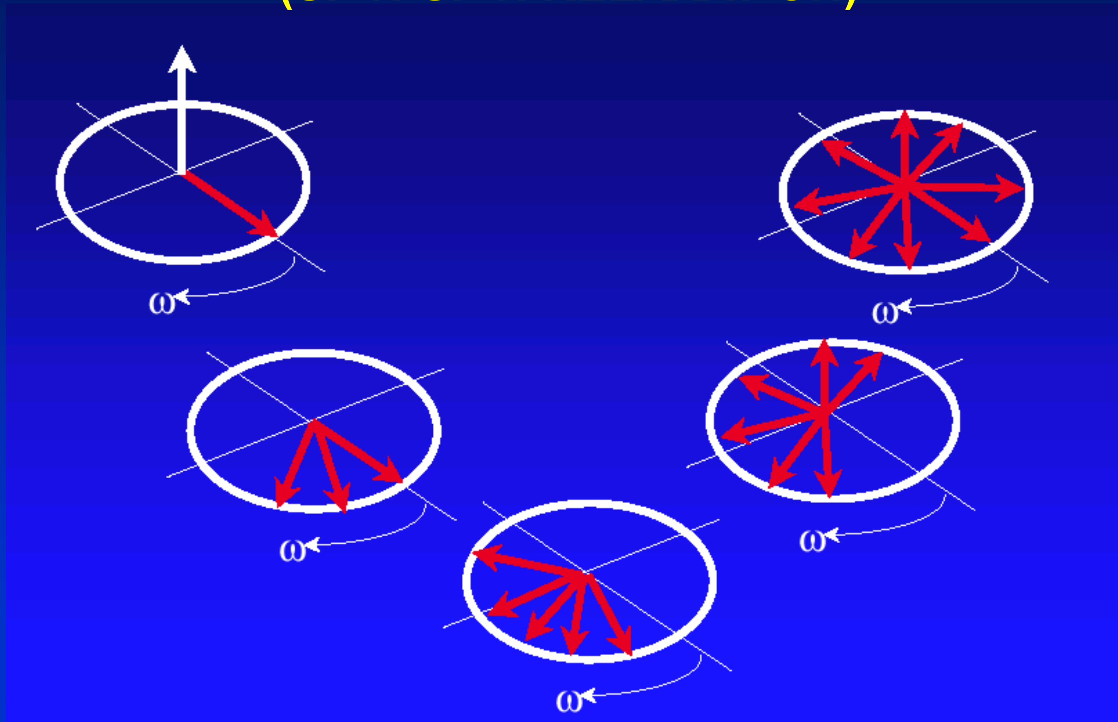
- **A magnetic receptor to measured the spin response**



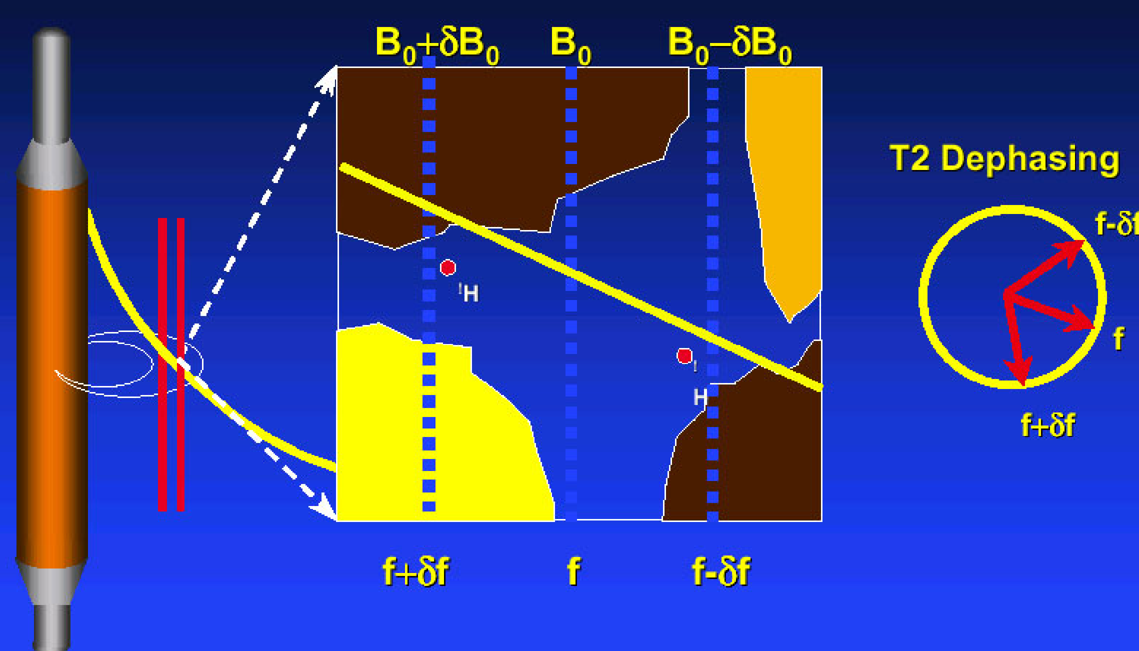

NMR is a Form of
Radio-Frequency Spectroscopy
excitation:
rf pulse at frequency ν_{rf}
impulse response:
$\cos\{2\pi\nu_L t\}\ \exp\{-(t/T_2)^b/b\}$
t
t
t
ν_{HF}
z
B_0
M
ν_L
y
x
10^{23} nuclear magnets
Σ = M
Spectro-meter
$\omega_0 = \gamma|B_0|$
resonance frequency
$\omega_0 = 2\pi\nu_0$
B_0
atomic nuclei
spectrometer
atomic nuclei in a magnetic field


NMR EXPERIMENTAL TIMING
M ∥ to Bo (longitudinal component)
Mo
0
$M_{\parallel} \propto 1 - \exp(-time/T_1)$
T_1 = 400 msec
TW
M ⊥ to Bo (transverse component)
Mo
0
$M_{\perp} \propto \exp(-time/T_2)$
T_2 = 250 msec
TE
TX
RF field
B1
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
time, seconds
adapted from Murphy, D.P., World Oil, April 1995

NMR DEPHASING OF SPINS
(SPIN-SPIN RELAXATION)



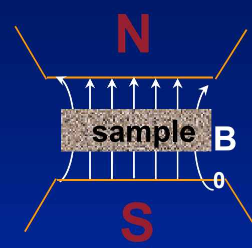
GRADIENT FIELD MEASUREMENTS
(SPATIAL GRADIENT IN THE STATIC MAGNETIC FIELD)
DEPHASING EFFECT



EXTERNAL and INTERNAL FIELD GRADIENTS

External Gradient

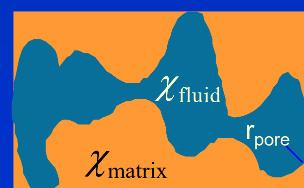
- Depends on the magnets' configuration. Negligible in laboratory experiments.



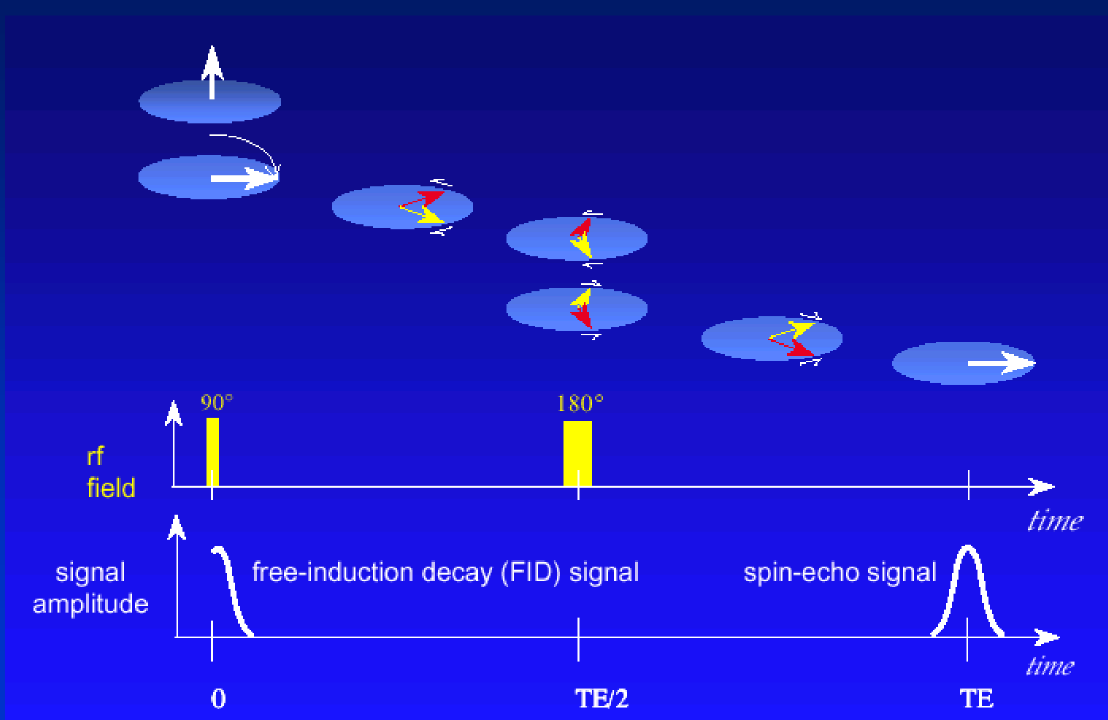
Internal Gradient

$$G \sim \frac{\Delta\chi \cdot B_0}{r_{pore}}$$

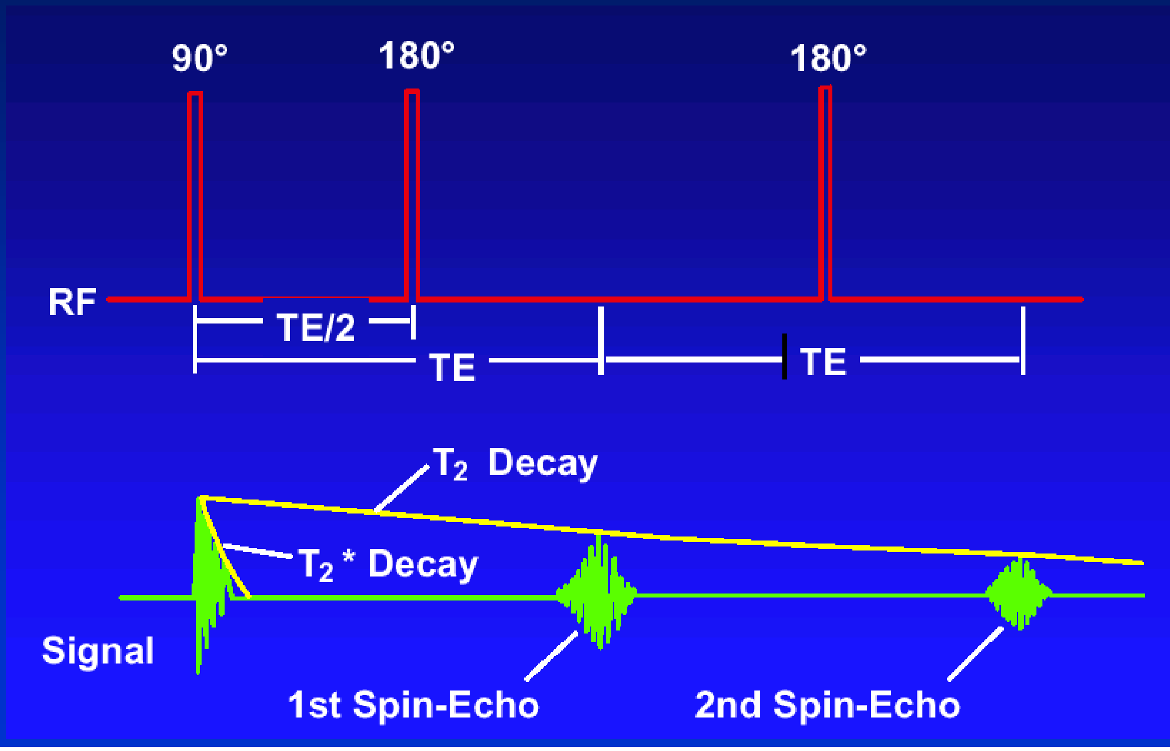
- Arises because of the difference in magnetic susceptibility between the matrix and the fluid.
- Depends on both the pore geometry and the type of rock.
- Important in porous media.
- Proportional to the RF frequency



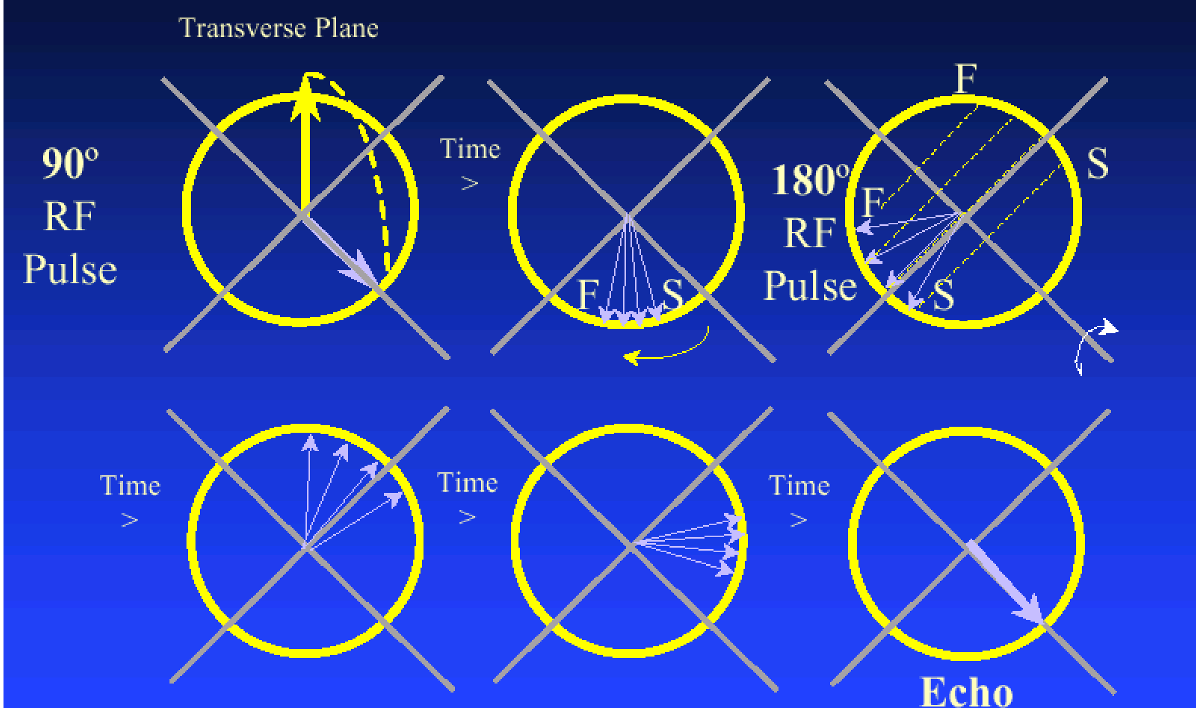
A SINGLE SPIN ECHO

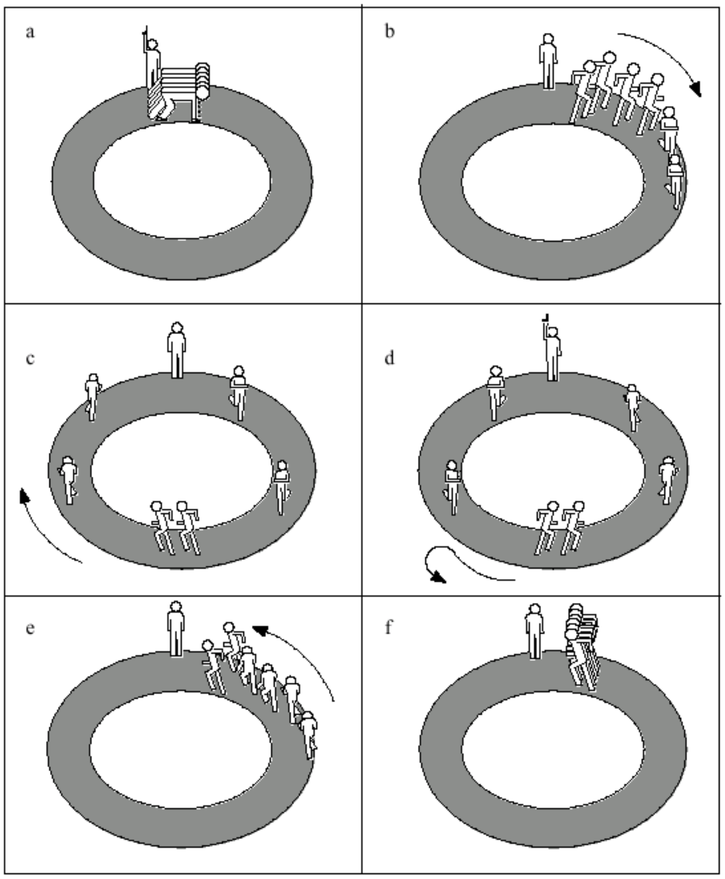


NMR SPIN ECHO SEQUENCE (CPMG SEQUENCE)



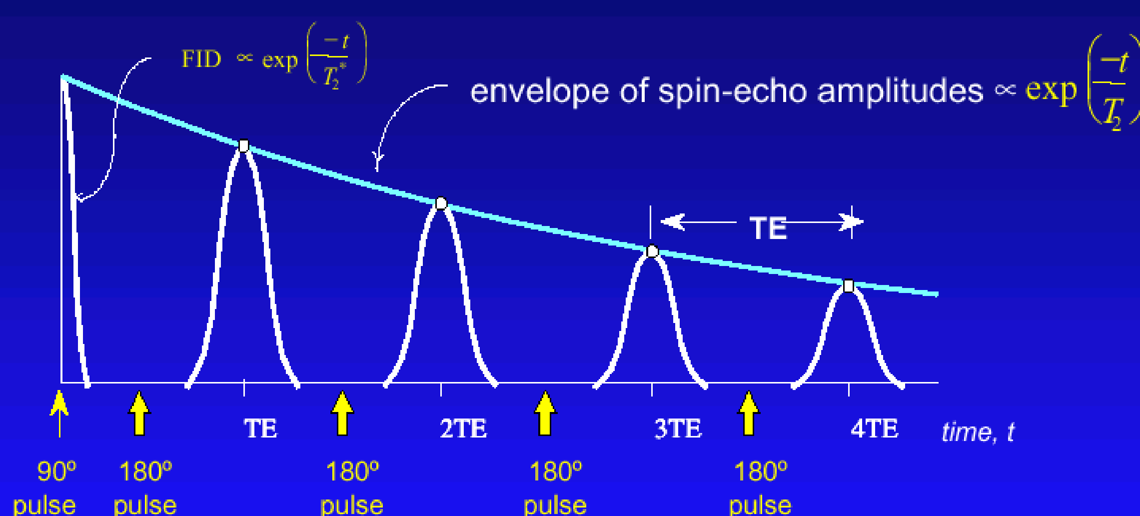
NMR SPIN ECHO SEQUENCE (CPMG SEQUENCE)





THE PROCESS OF DEPHASING: A RUNNER'S ANALOGY

IDEALIZED CMPG SPIN-ECHO TRAIN



SUMMARY: CMPG SPIN ECHO SEQUENCE

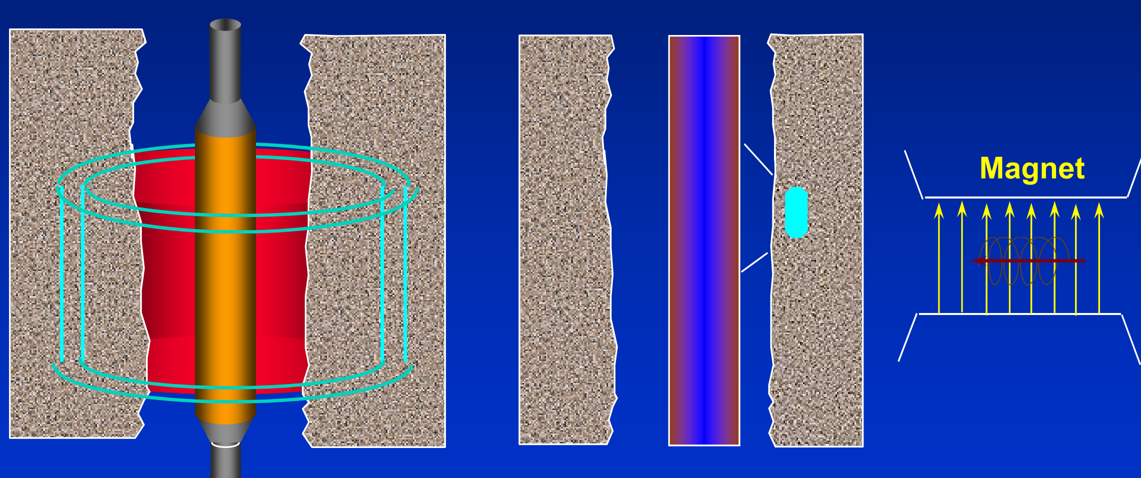
Step 1:	B_0 →	Proton alignment
Step 2:	B_1 →	Proton 90° tipping result: precession
Step 3:	Precessing and dephasing as a result of B_0 inhomogeneity /gradient field result: partial loss of synchronization	
Step 4:	B_1 →180° refocusing result: partial reversible dephasing, signal measured as „spin echo“	

... step by step coherent magnetization decreases ---> relaxation

COMMERCIAL NMR WIRELINE TOOLS

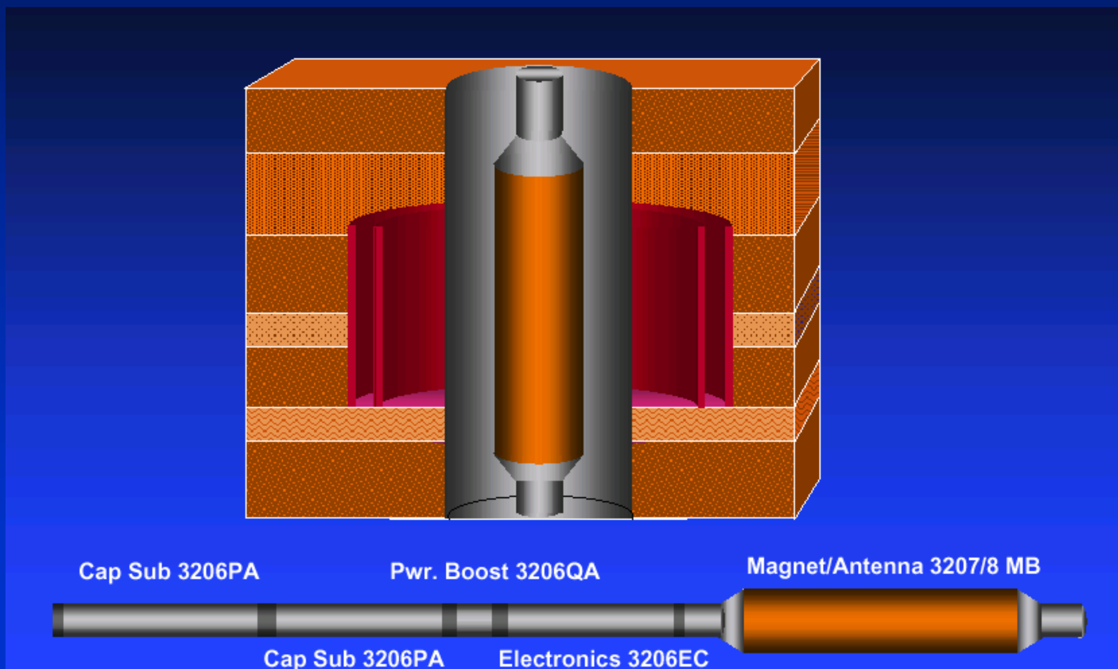
MRIL

CMR



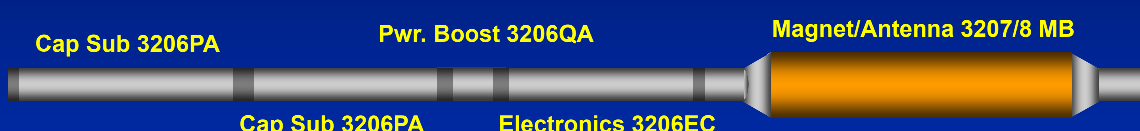
Gradient field vs. Homogeneous B_0

MODERN MRIL WIRELINE TOOL (MANDREL TOOL)

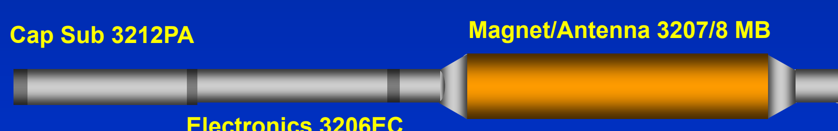


WIRELINE MRIL TOOL

NUMAR C/TP Configuration

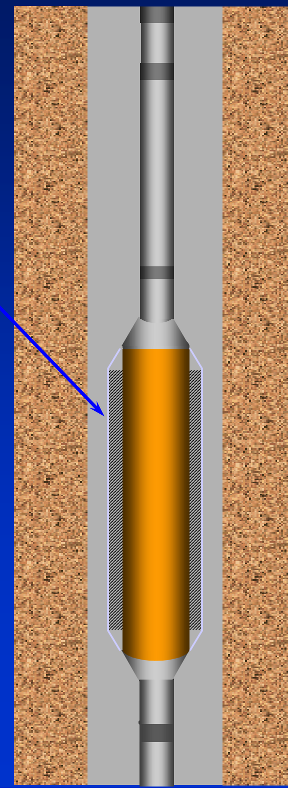


Baker Atlas C/TP Configuration 20’ shorter



WIRELINE MRIL TOOL: Mud Excluder

Fiberglass sleeve to displace mud

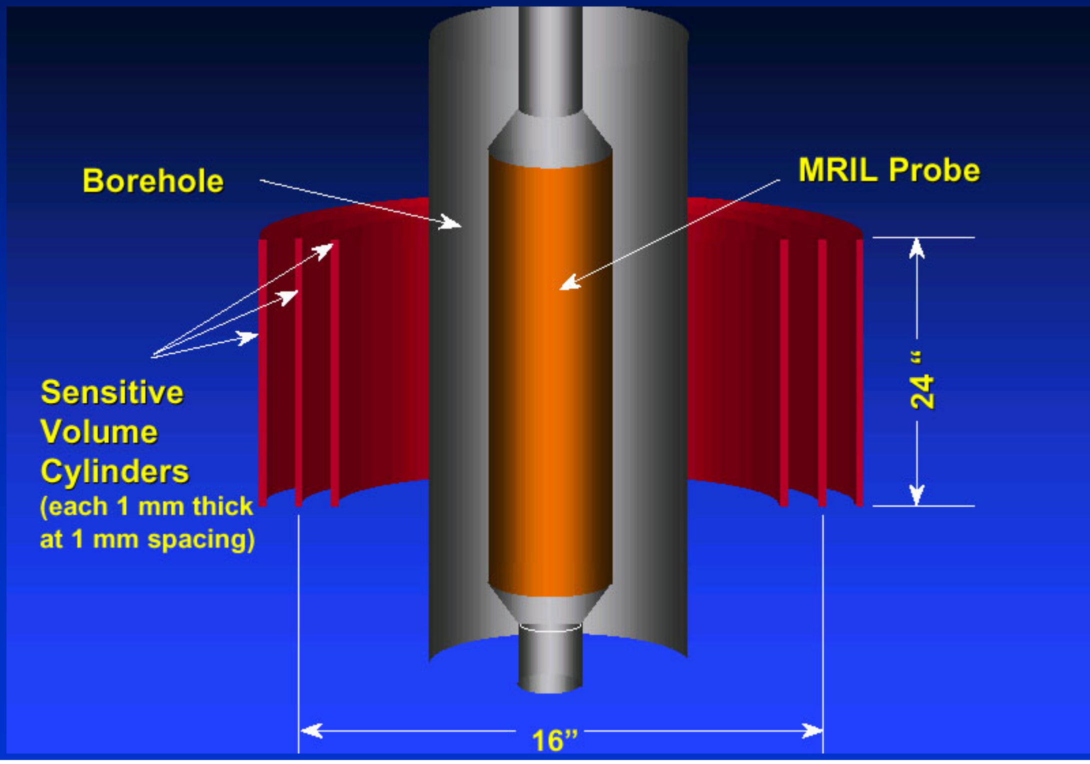


Sizes: 7.25” and 9”

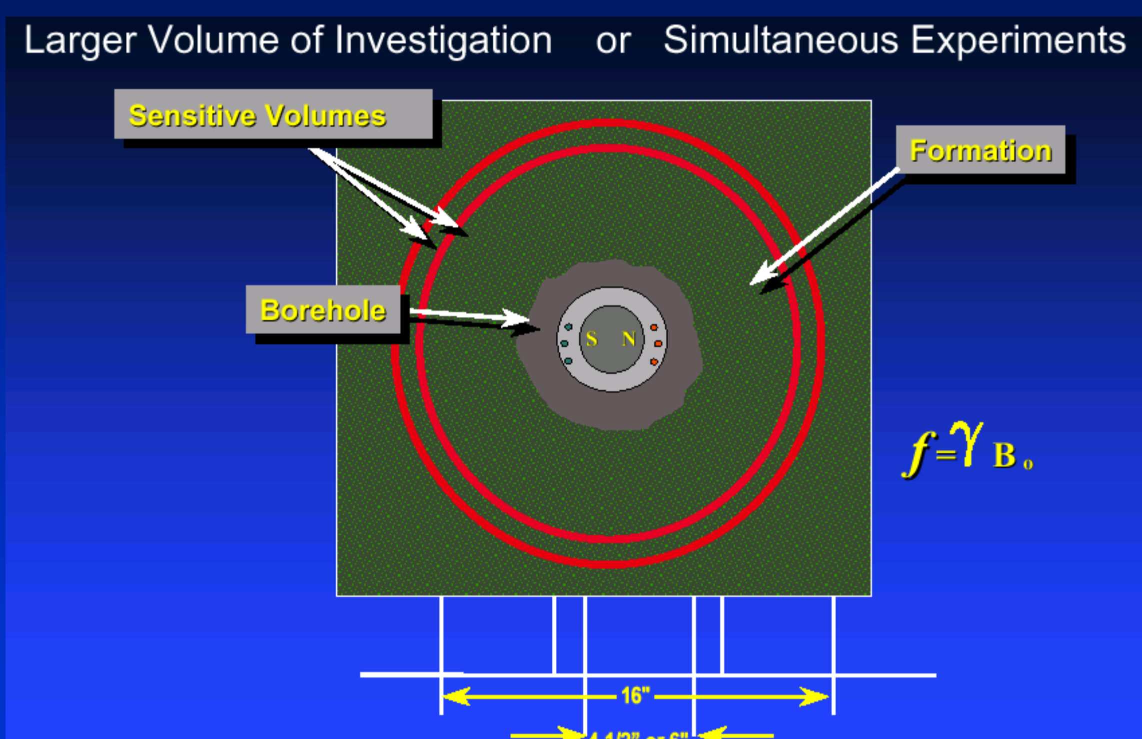
MRIL TOOL SPECIFICATIONS:

- Maximum Operating Temperature- 310°F (155°C) for 5 hours
- Maximum Pressure-20,000 psi (137MPa)
- Tool Diameter-4.5" magnet and 6" magnet
- Measuring Range-0 p.u. to 100 p.u.
- Accuracy (MHPI, MBVM, MBVI) ±5% or 1 p.u.
- Repeatability (MPHI, MBVM, MBVI) 1 p.u. standard deviation of measured porosity
- Logging Speed Dependent on FormationT1 and Sampling Rate
- Borehole Diameter Range
- - 4.5" magnet - 5" to 7.5" BHD
- - 6" magnet-7.5" to 12.25" BHD
- Minimum Vertical Resolution-24 inch aperture
- Maximum Borehole Deviation-90° deviation (PCL)

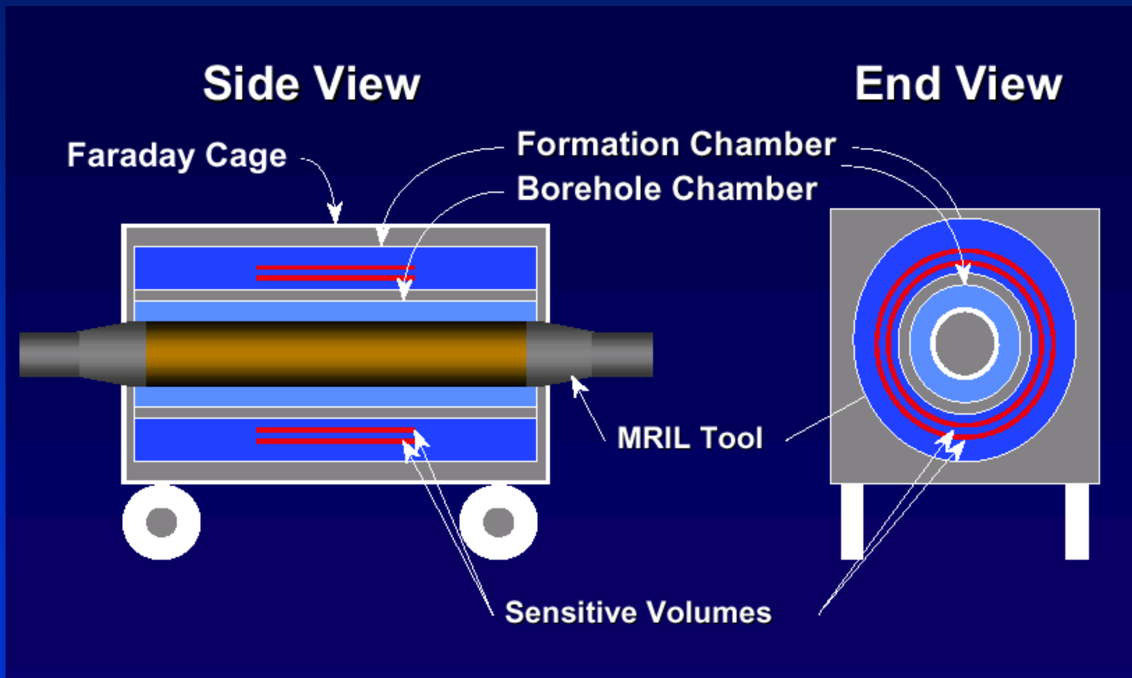
MULTIPLE FREQUENCY, HIGH RESOLUTION MRIL TOOL



MULTIPLE FREQUENCIES



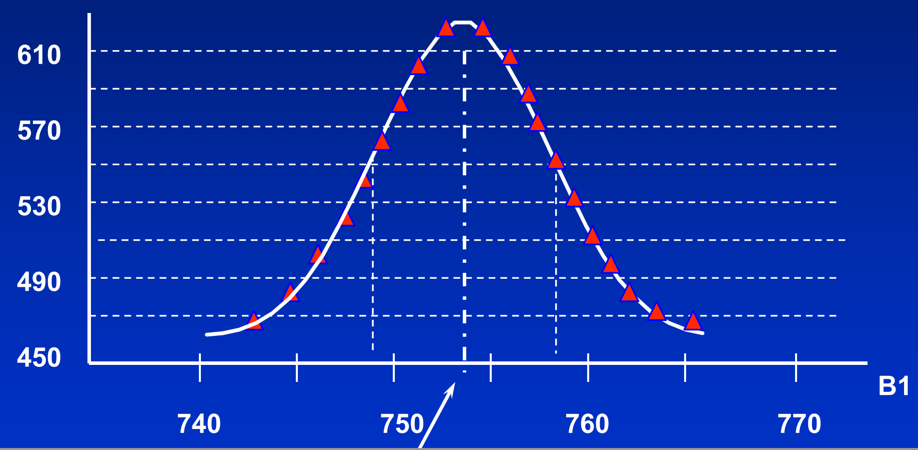
CALIBRATION



MRIL CALIBRATION

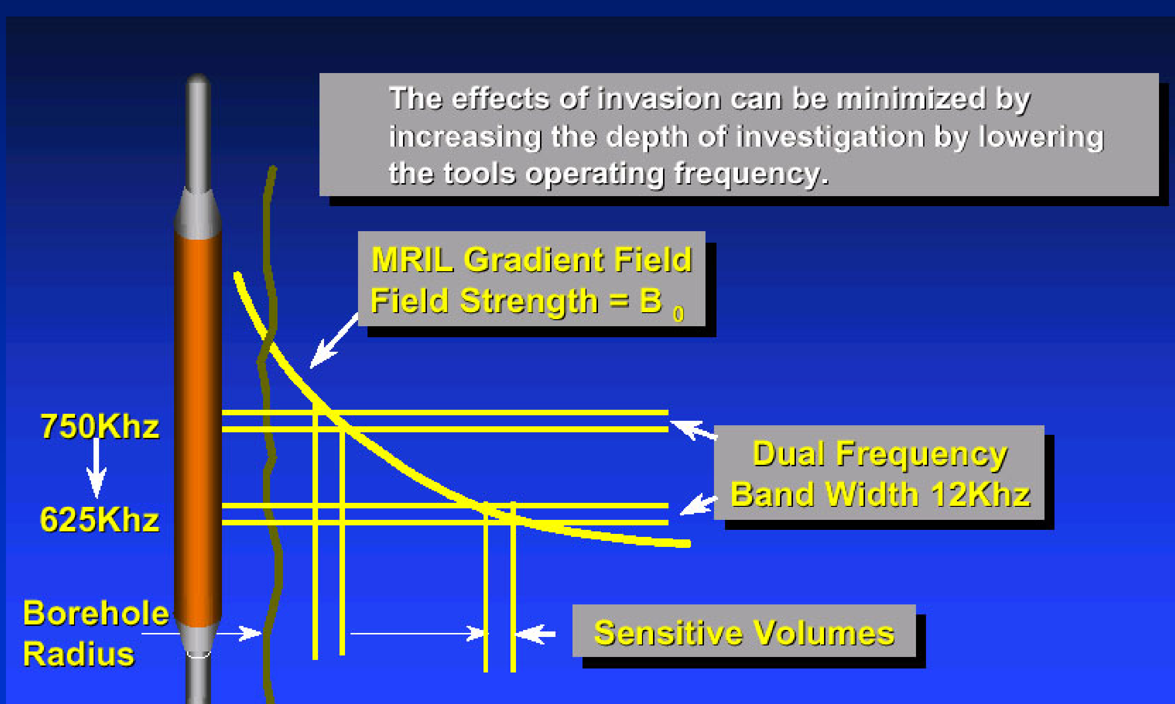
- The calibration is performed in a fiberglass borehole and formation simulator enclosed in a Faraday cage. (Frequency of 60 - 90 days)
- It is a single point calibration for 100% porosity in fresh water (HI = 1).
- The calibrator is also logged to check tool stability at 100% +/- 2% before and after job.
- At the well site the tool is checked with a “Electronics Verifier”. The box simulates the magnet to perform a check on the transmitter and electronics functions. Continuity and insolation checks are done on the magnat/antenna .

MRIL CALIBRATION: FREQUENCY SWEEP

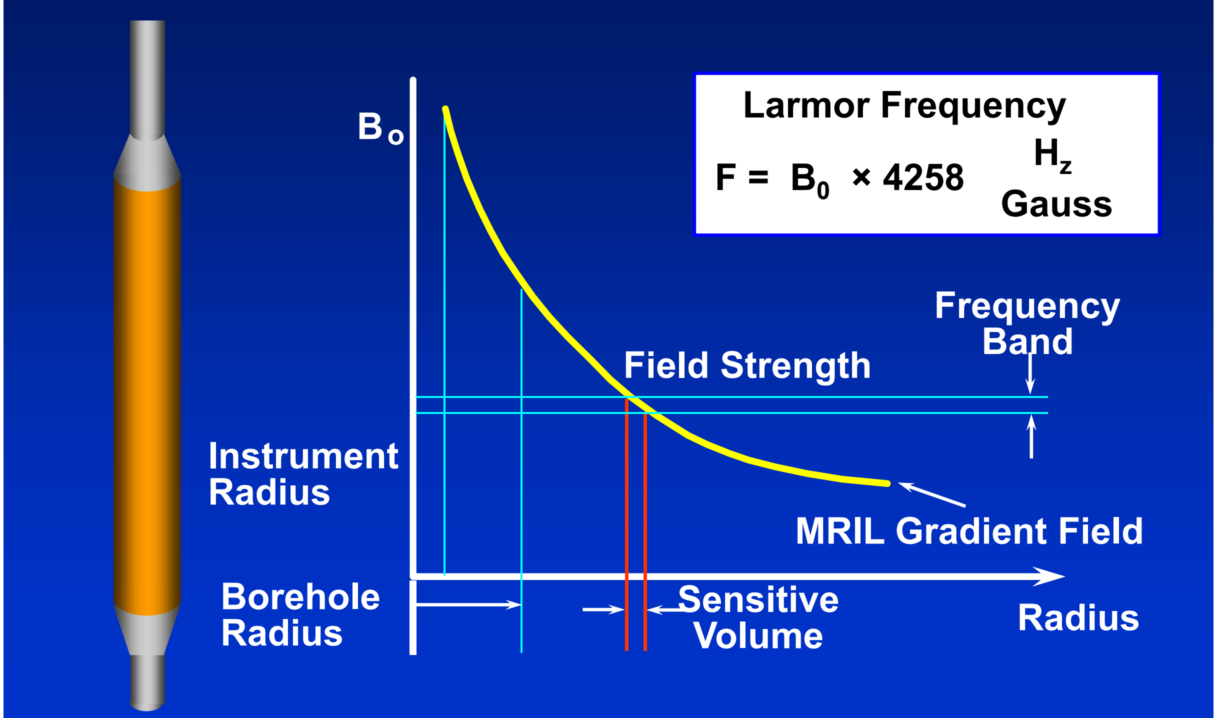


Peak Frequency : In dual frequency mode the MRIL tool will operate at the peak frequency +/- 6kHz.

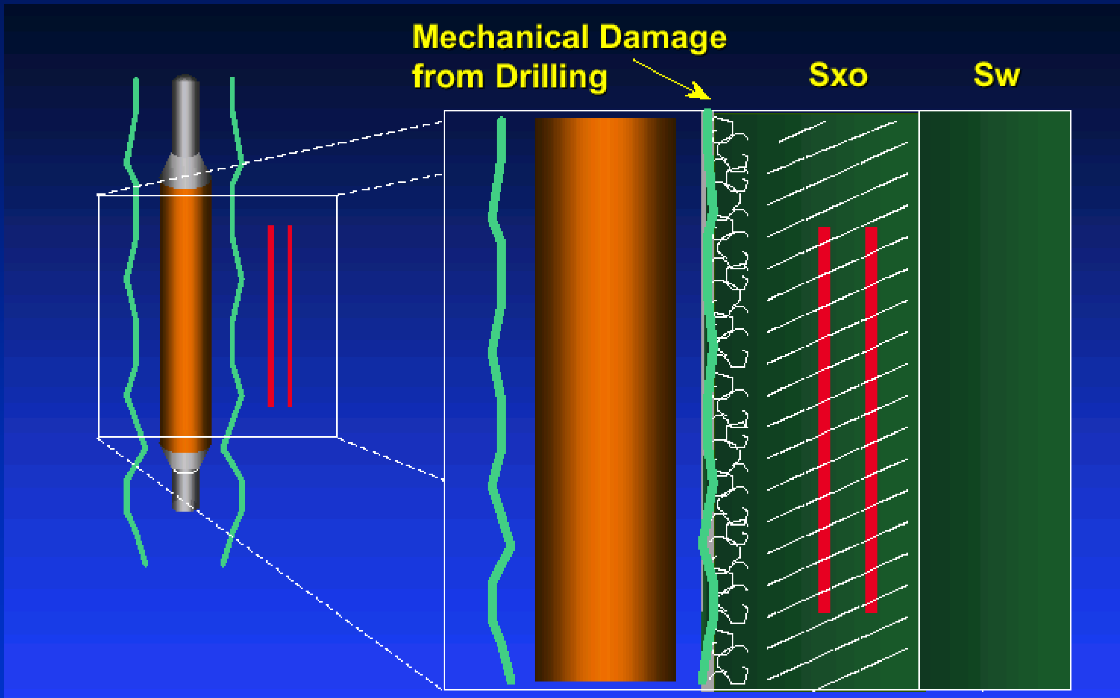
MRIL SENSITIVITY VOLUME



MRIL SENSITIVITY VOLUME

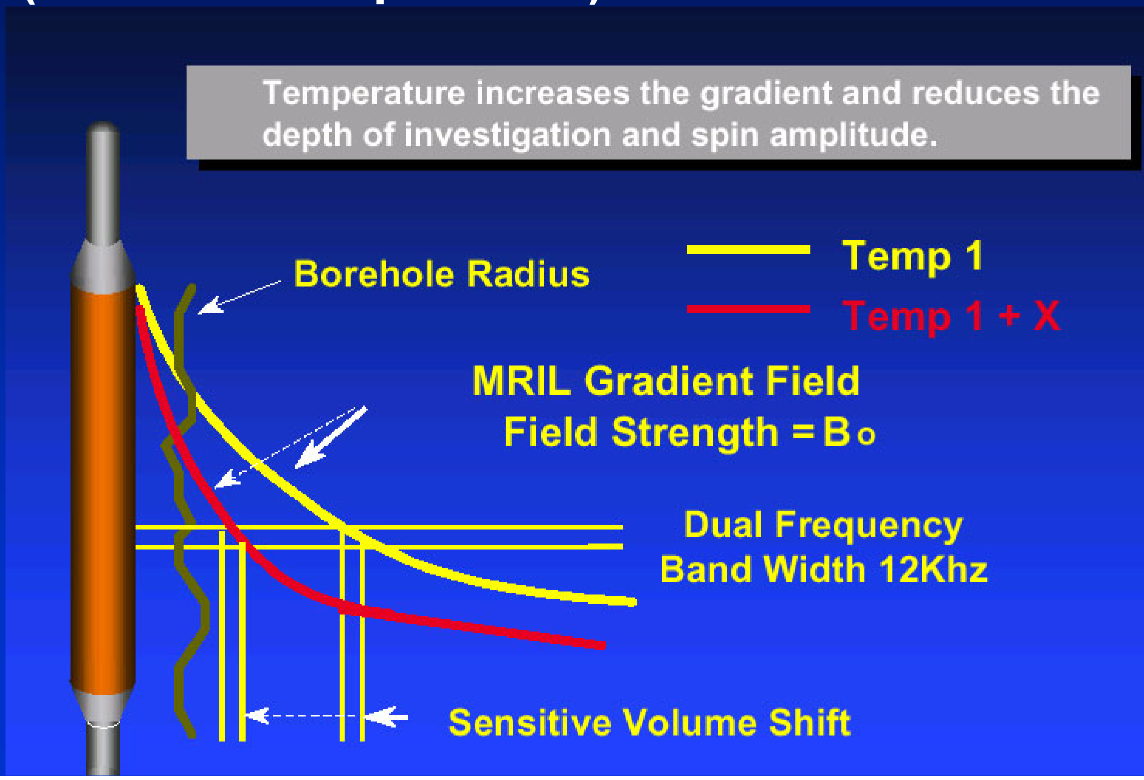


SENSITIVITY VOLUME IN THE INVADED ZONE

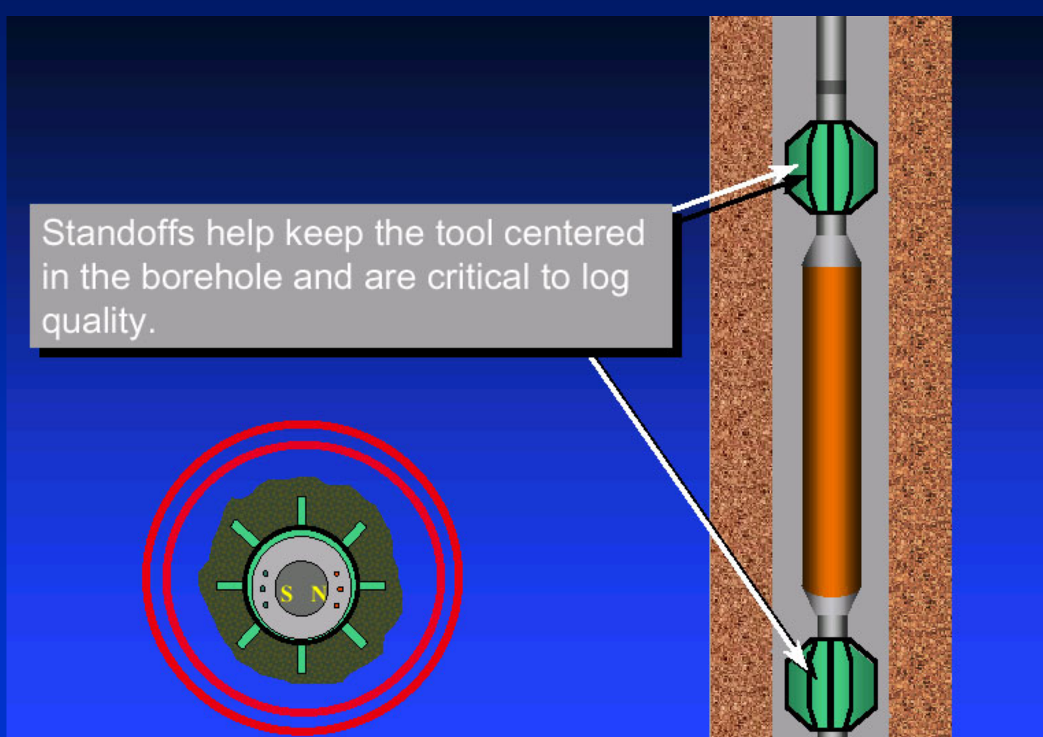


MRIL primarily measures in the flushed zone where invasion alters the native fluid saturation. Additives in the mud system may alter wetability.

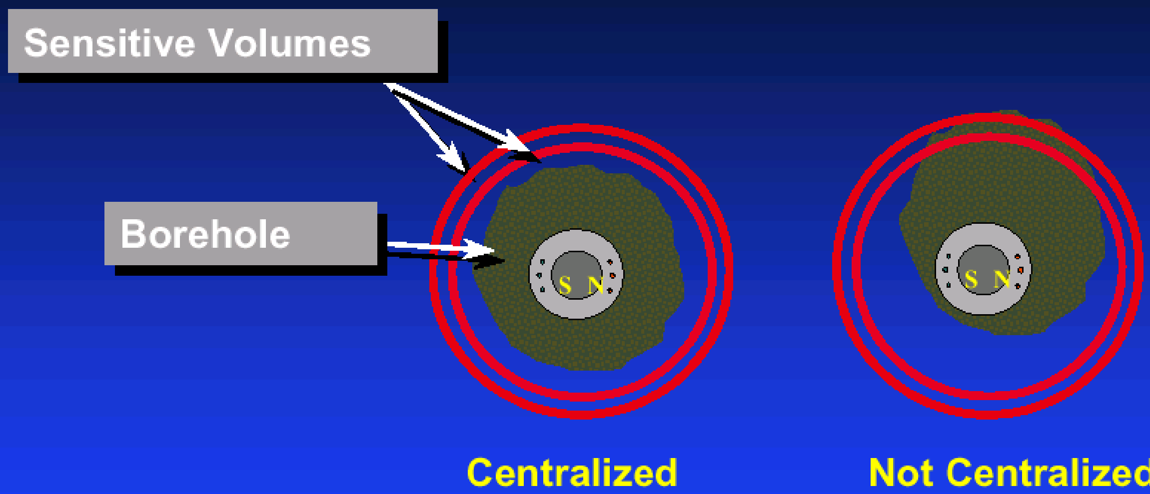
MRIL SENSITIVITY VOLUME
(Effect of Temperature)



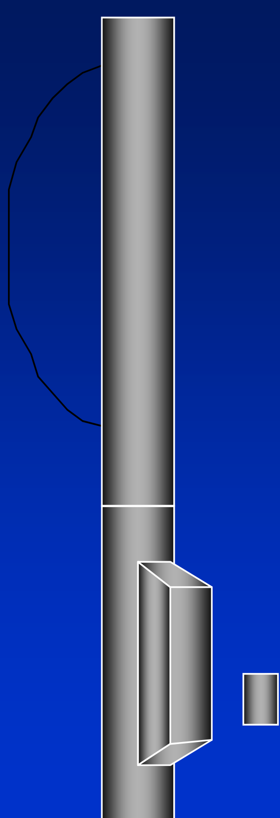
CENTRALIZATION



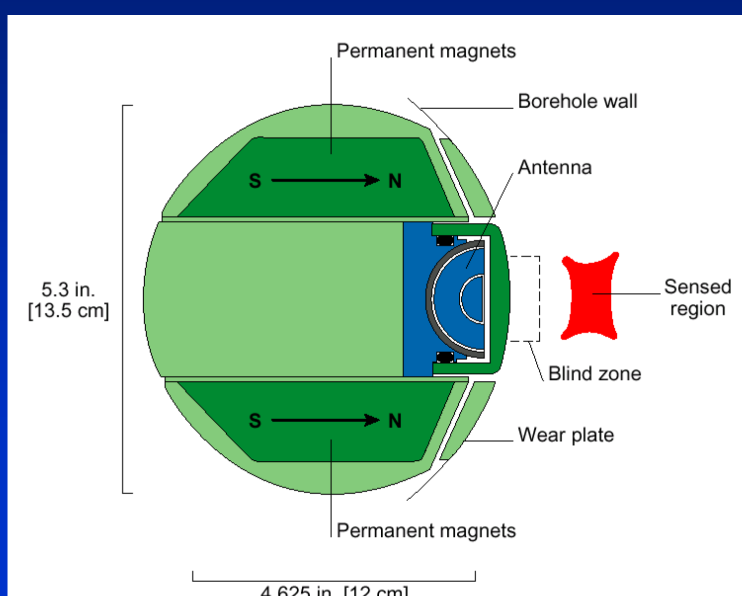
ECCENTRICITY EFFECT

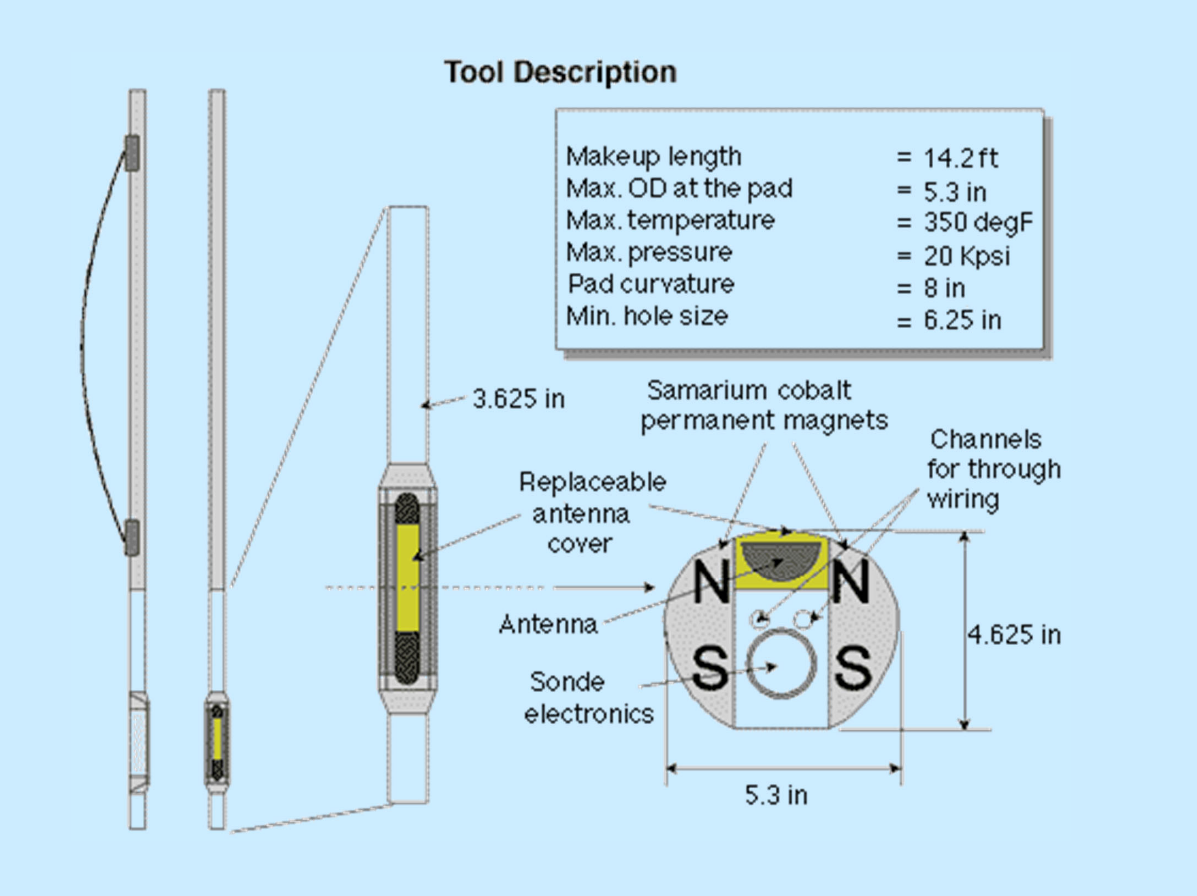


Decentralization results in a sensitive volume that intersects the borehole.

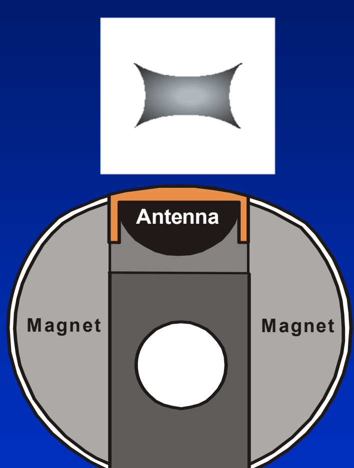


SCHLUMBERGER'S CMR, CMR-200, CMR-Plus

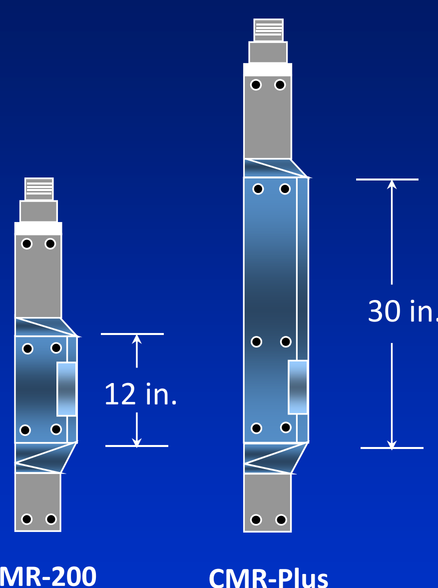




SCHLUMBERGER'S CMR TOOLS

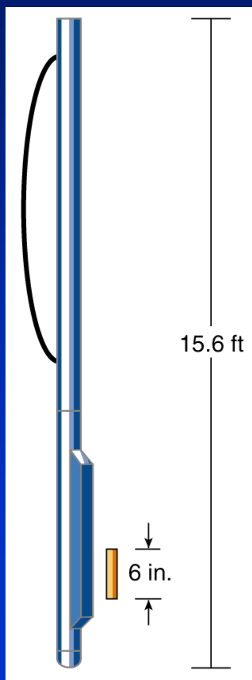


CMR-200 and CMR-Plus
Sonde Cross Section



Both tools use the same cartridge but the
CMR-Plus has an extra 18 inch magnet section

TOOL SPECIFICATIONS



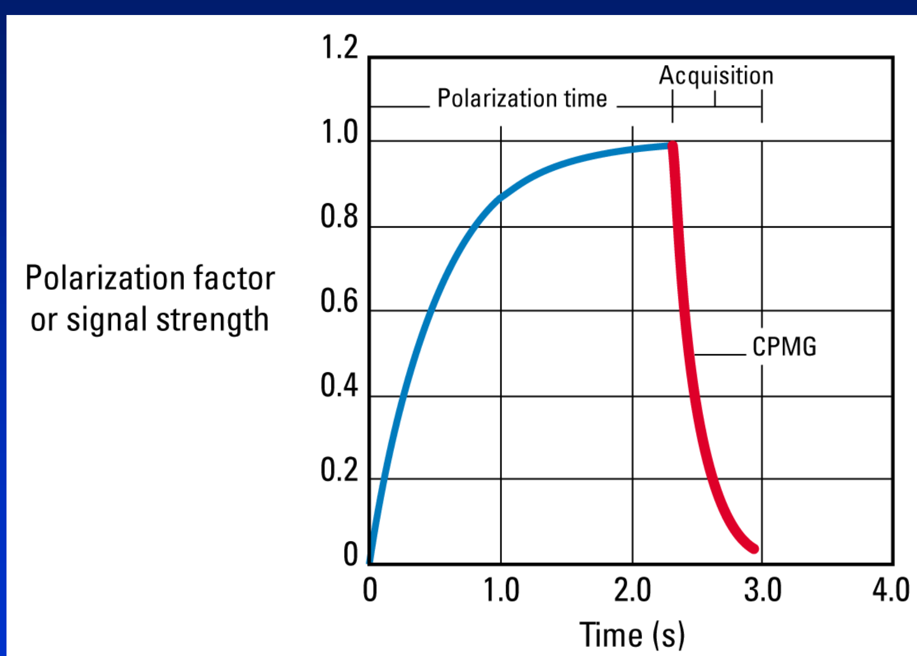
CMR-Plus

- Logging speed
  - Long T_1 — 800 ft/hr
  - Short T_1 — 3600 ft/hr
- Length — 15.6 ft
- Weight w/ bowspring — 413 lbm
- Minimum hole size — $5\frac{7}{8}$ in.
- Vertical resolution (three-level) — 24 in.

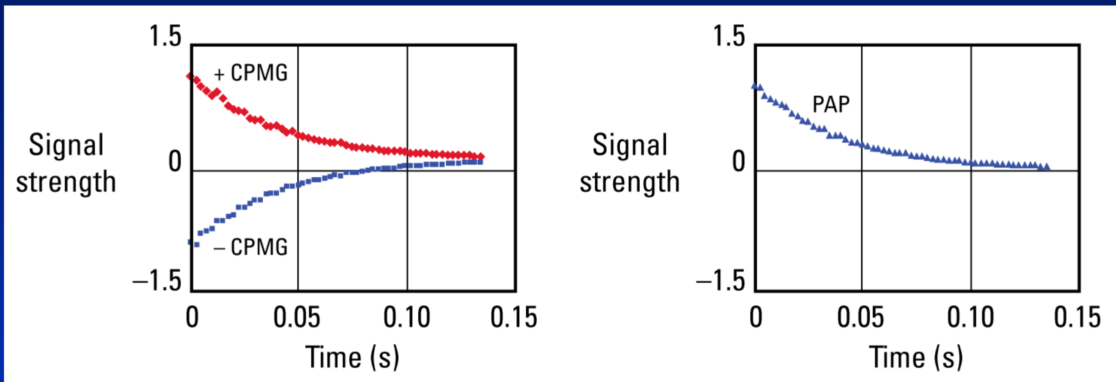
CMR-200 and CMR-Plus

- Measurement aperture — 6 in.
- Max pressure — 20 and 25 kpsi
- Max temperature — 350°F
- Echo spacing — 200 μs
- Depth of investigation — 1.1 in.
- Mud resistivity — No limit

NMR PULSE SEQUENCE



PHASE-ALTERNATED PAIR

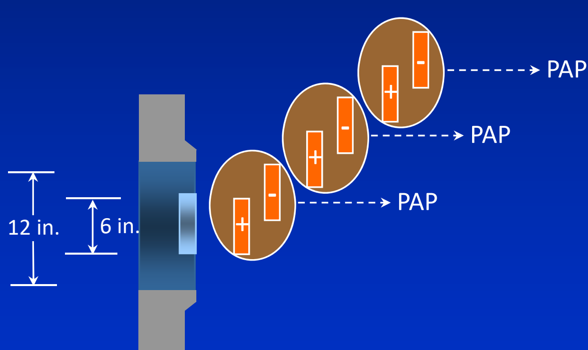


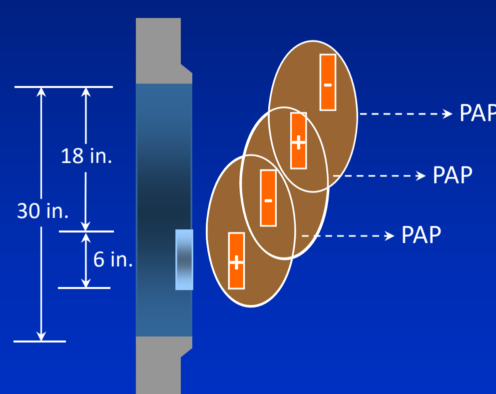
- Two CPMGs of opposite phase
- A phase-alternated pair (PAP) cancels electronic offsets and 180° ringing.

Overlapping vs. Non-Overlapping CPMGs

CMR-200 or CMR-Plus

CMR-Plus





Overlapping CPMGs

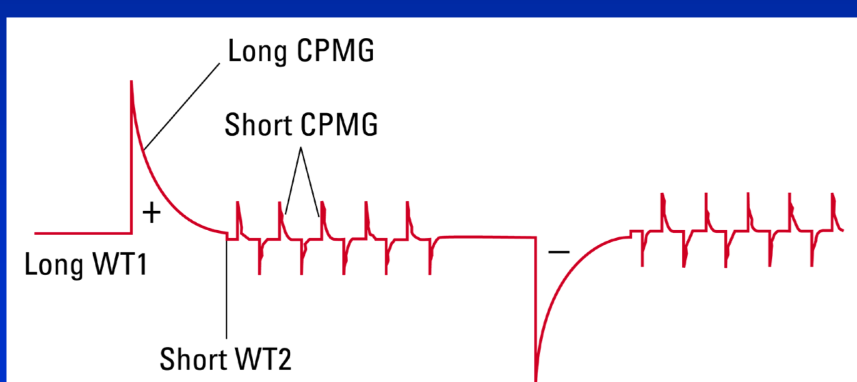
Non-Overlapping CPMGs

Typical CMR-Plus Acquisition Sequences and Logging Speeds

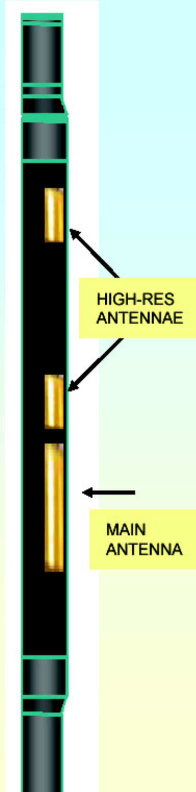
T_1	Polarization Time (s)	Number of Echoes	Sample Interval (in.)	Logging Speed (ft/hr) Standard	EPM
Short (0–0.5 s)	1.4	600	7.5	3600	1800
Medium (1–2 s)	7.3	1800	7.5	1500	1200
Long (3–4 s)	13.5	3000	7.5	800	700

Enhanced Precision Mode

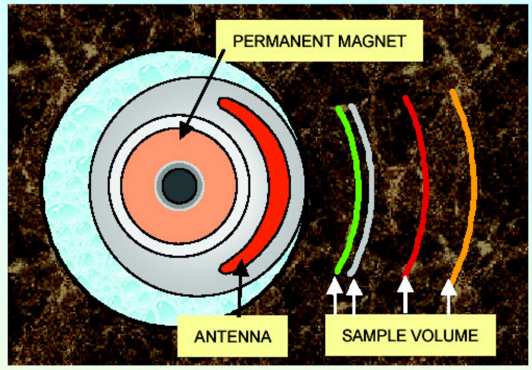
- Special multi-wait-time (MWT) pulse sequence
  - One long wait-time subsequence (WT1 = 1–12 s) (measures all T_2 components)
  - Ten short wait-time subsequences (WT2 = 0.02 s, 30 echoes) (measure the early T_2 components)



Schlumberger's Latest Wireline NMR Tool



MRX Design



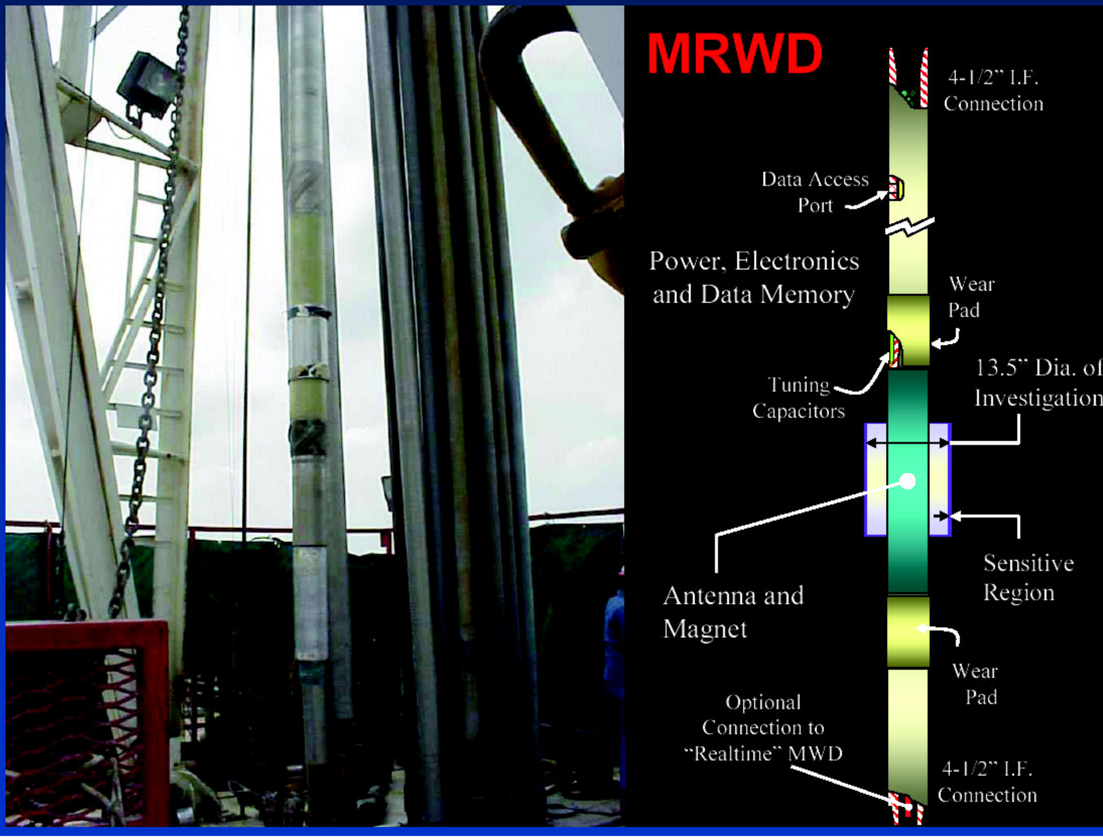
MRX: Eccentered Gradient design

- Sample volume in thin shells
- <u>Deeper</u> and well defined DOI
- <u>Depth log MRF</u>
- Tuning is simple
- High-end NMR applications

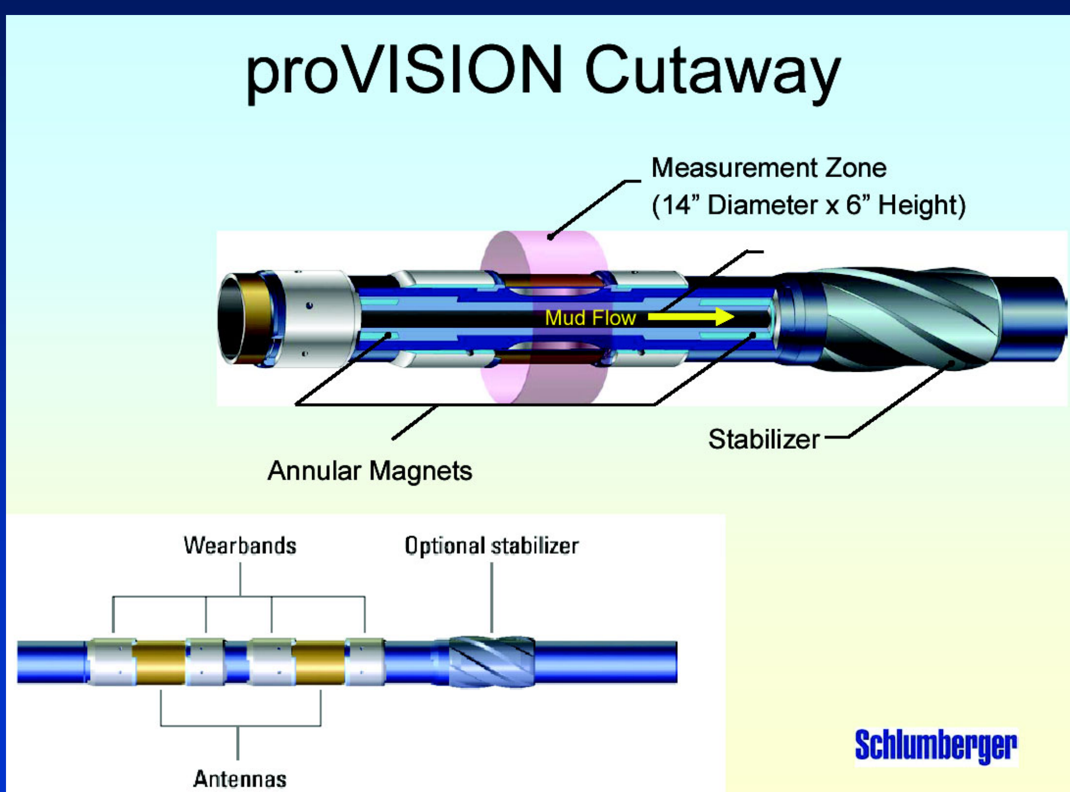
NMR Wireline Tool Summary

Vendor		Halliburton		Schlumberger		BakerHughes
Toolname		MRIL Prime		CMR+	MRX	MREx
Diameter	in	6	4.7/8	6	5	5
Borehole min	in	7	6	6	5.7/8	5.7/8
Borehole max	in	16	8.5	na	na	na
DOI	in	~ 4		1	1.5 - 4	2.4 - 4.4
Max temp	F	350		350	300	350
Gradient	G/cm	18		wide	30 - 10	34 - 11
Frequency	kHz	600		2200	1000-500	900-450
# shells		9		1	$\geq$ 4	$\geq$ 6
Antenna length	in	24		6	7.5	24
Shortest TE	ms	0.6		0.2	0.45	0.4
Max # echoes		1000		8000	(>) 1000	(>) 1000
Max logging speed	ft/hr	1500		1800	1800	1400
Position		centred		pad	pad	pad
Mud effect on noise		strong		low	low	low

Logging-While-Drilling NMR

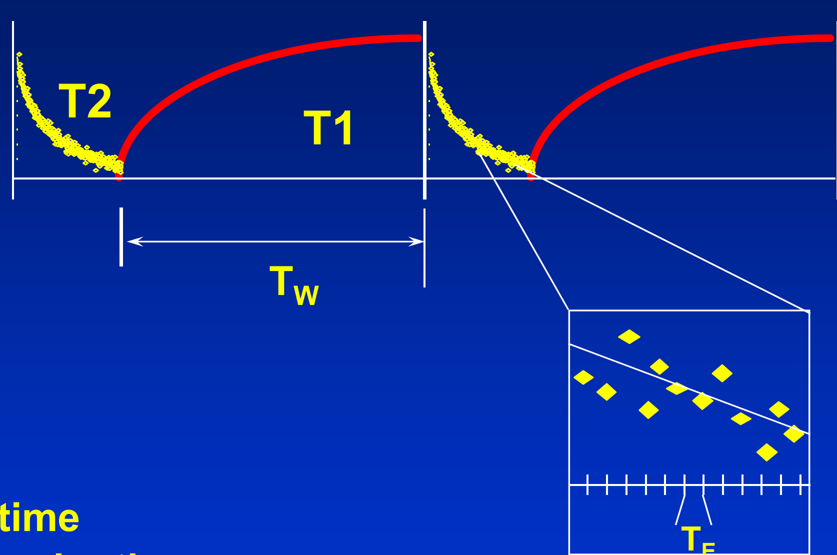


Logging-While-Drilling NMR



BASIC INTERPRETATION
OF
NUCLEAR MAGNETIC RESONANCE
DATA

LONGITUDINAL AND TRANSVERSE RELAXATION



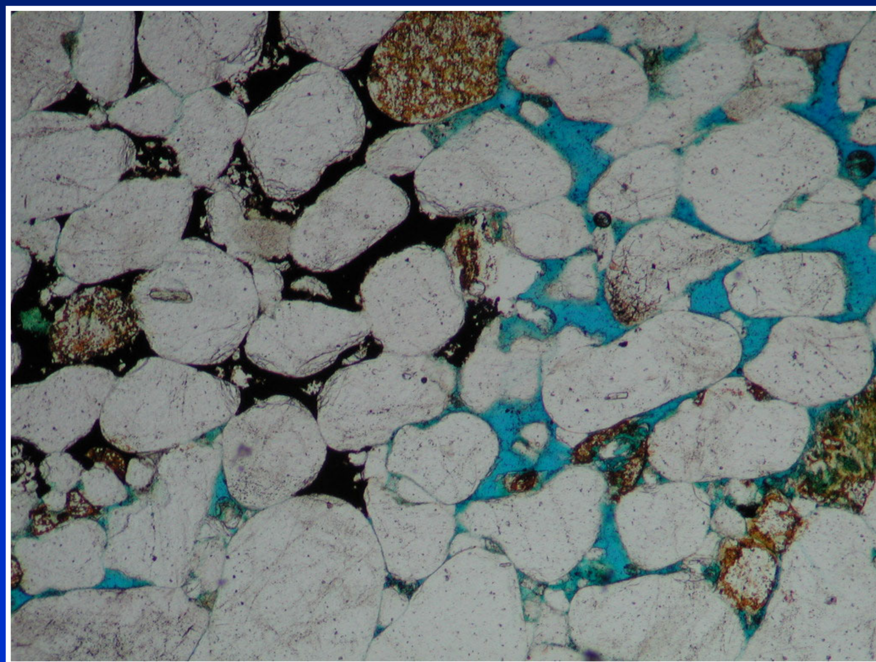
T_w= wait time

T_E= inter-echo time

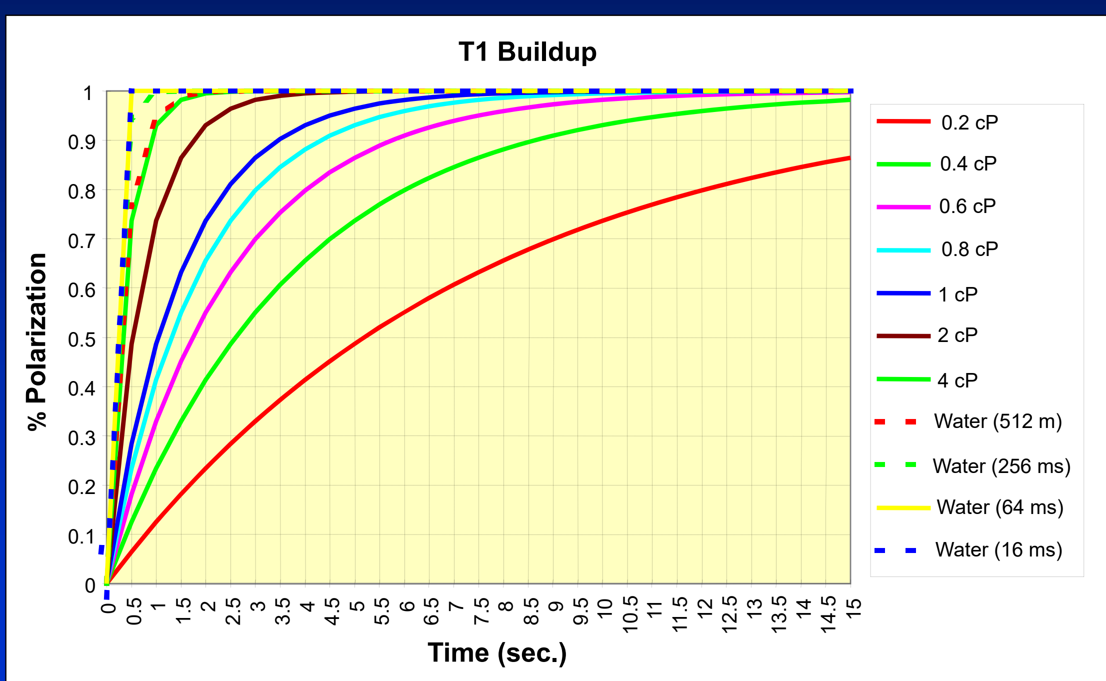
T1= Longitudinal magnetization build up

T2= Transverse magnetization decay

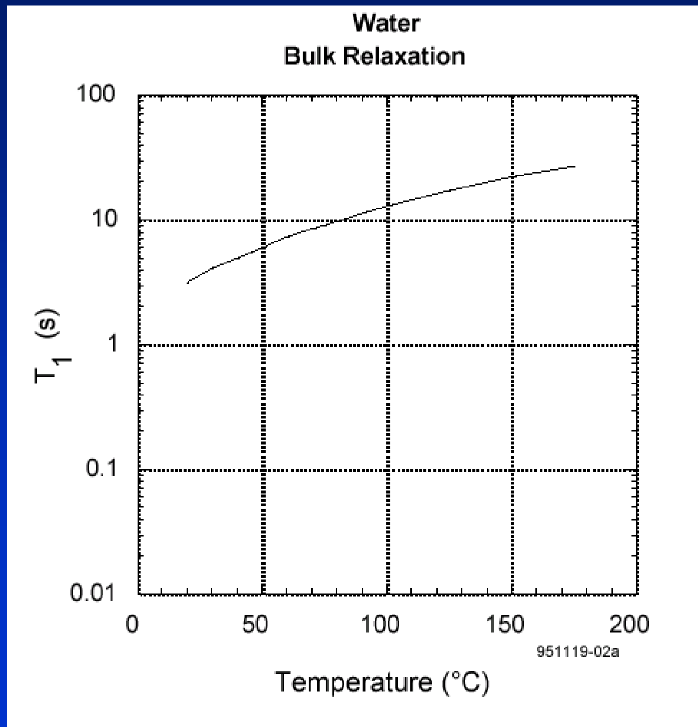
NMR Longitudinal Relaxation and Fluid Distribution in the Pore Space



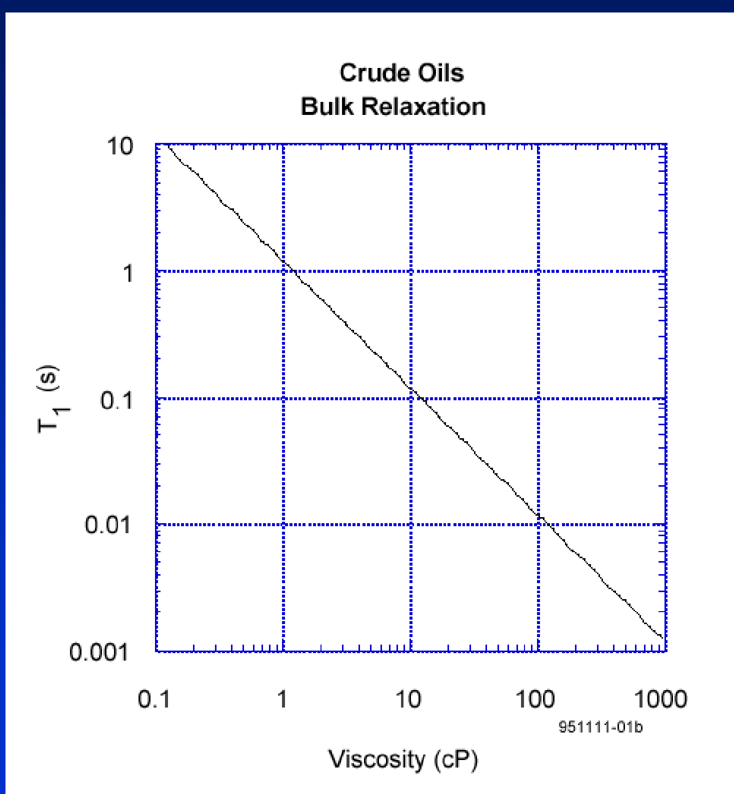
T1 BUILD-UP OF OILS

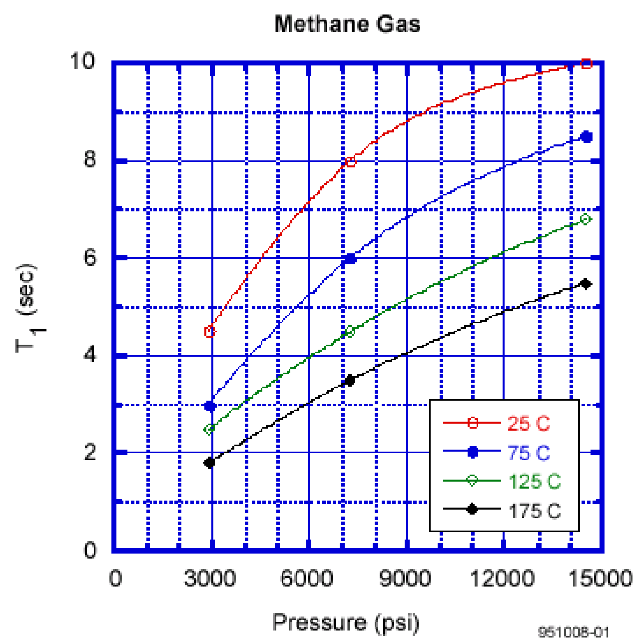


T1: TEMPERATURE DEPENDENCE



T1: CRUDE OILS

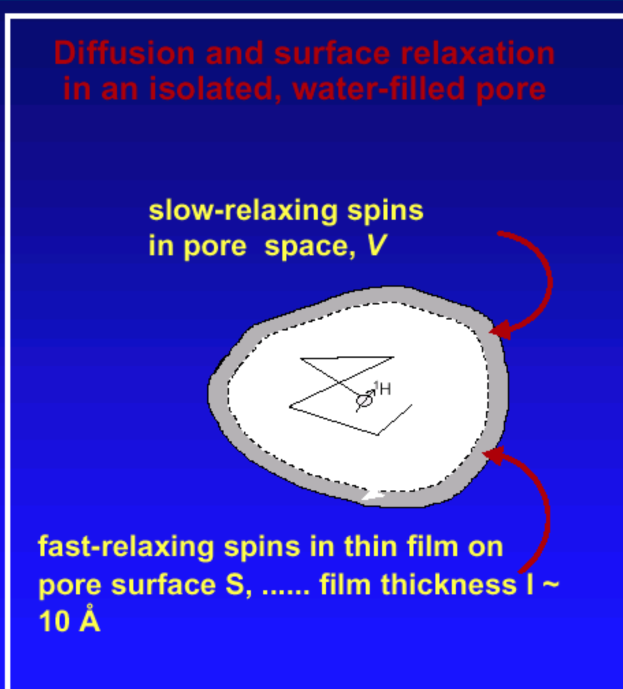




C.J. Gerritsma, P.H. Oosting, N.J. Trappeniers
"Proton Spin-Lattice Relaxation
and Self Diffusion in Methanes, II"
Physica, 51, 381-394 (1971)

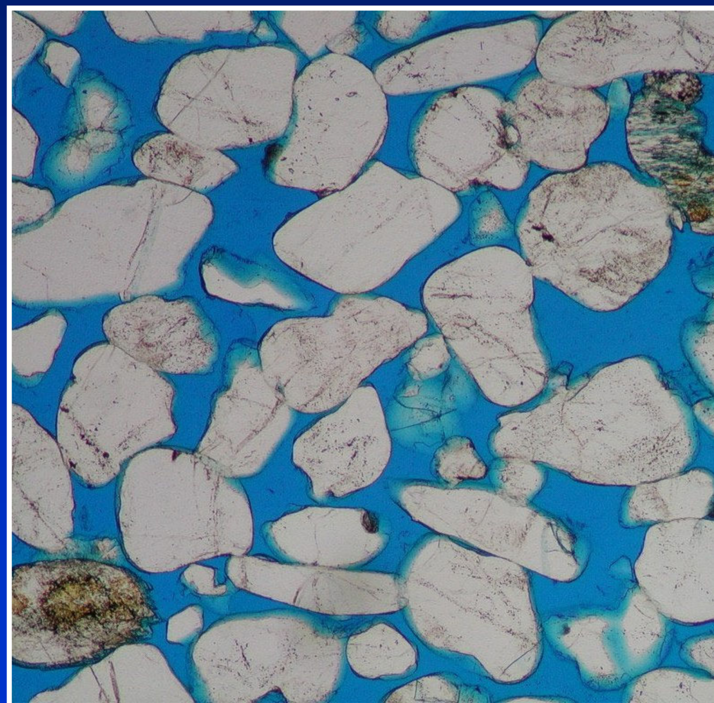
T1: PRESSURE DEPENDENCE

NMR TRANSVERSE RELAXATION IN WATER-FILLED PORES

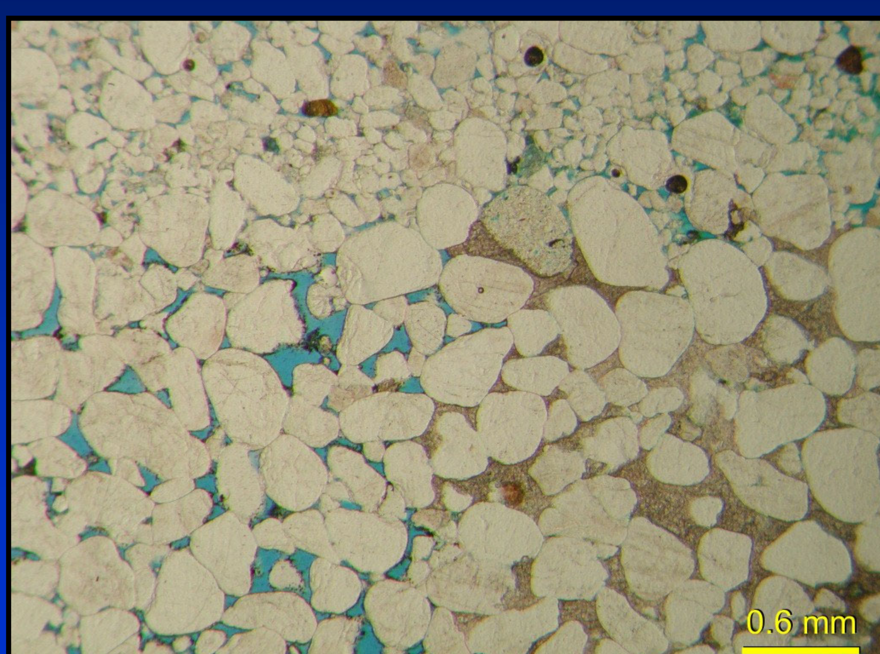


$$\frac{1}{T_2} = \rho \frac{S}{V} + \frac{1}{T_{2_b}} + \frac{1}{T_{2_D}}$$

NMR Transverse Relaxation and Pore Size Distribution

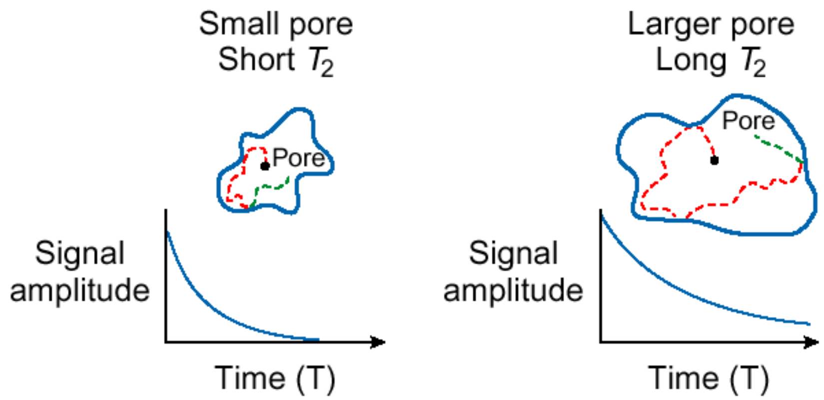


NMR Transverse Relaxation and Pore Size Distribution



TRANSVERSE RELAXATION

Amplitude Decay Explanation



$$1/T_2 = \rho(S/V)$$

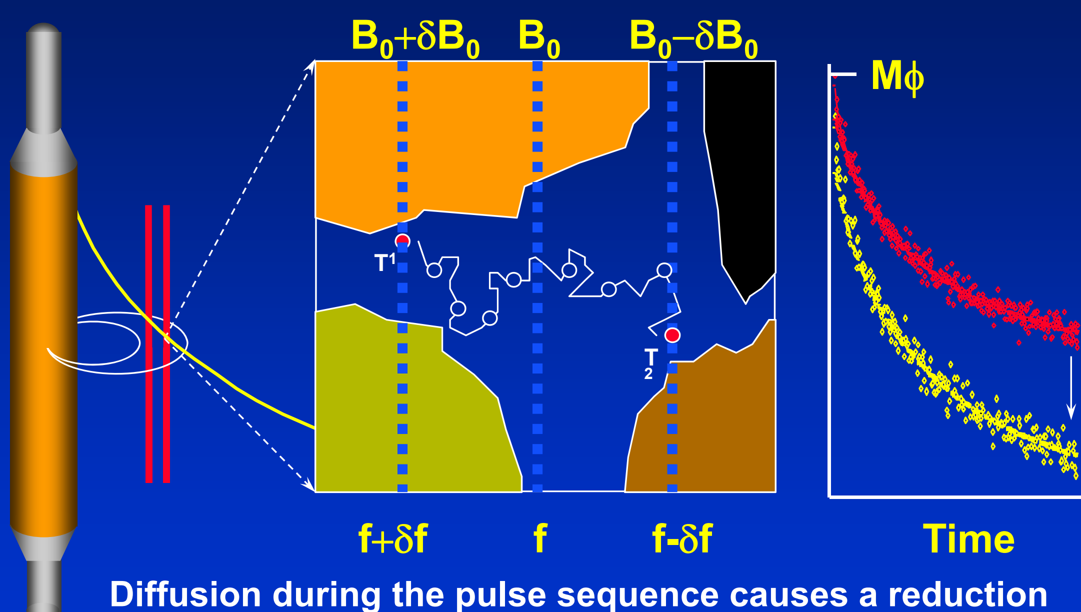
T_2 = Transverse relaxation time (msec)

S = Surface area of pore

V = Volume of pore

ρ = Surface relaxivity

Gradient Field and Diffusion



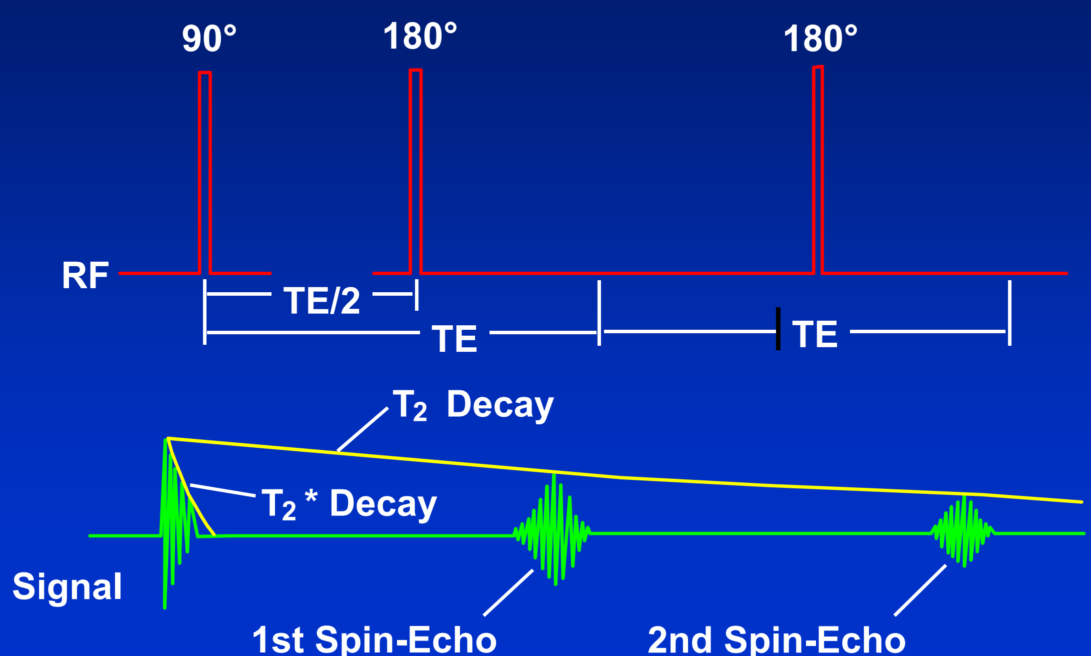
Diffusion during the pulse sequence causes a reduction in signal amplitude with time and decreases T2.

CARR-PURCELL
GRADIENT FIELD RELAXATION RATE

$$\frac{1}{T_{2(CPMG)}} = \frac{1}{T_2} + \frac{D(\gamma\ G\ T_E)^2}{12}$$

T_2 = Intrinsic Relaxation Rate (sec)
G = Static Magnetic Field Gradient (gauss/cm)
γ = Gyromagnetic Ratio (0.678 radians/gauss)
T_E = Pulse Echo Spacing (sec)
D = Diffusion Coefficient (cm^2/sec)

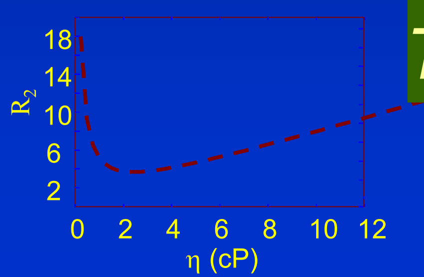
CARR-PURCELL
GRADIENT FIELD RELAXATION RATE



BULK (T2) and GRADIENT (D) DIFFUSIVITY Relationship with Fluid Viscosity

$$D = \frac{1.3T_K}{298\eta} \qquad T_{1bulk} \approx T_{2bulk} = \frac{1.2T_K}{298\eta}$$

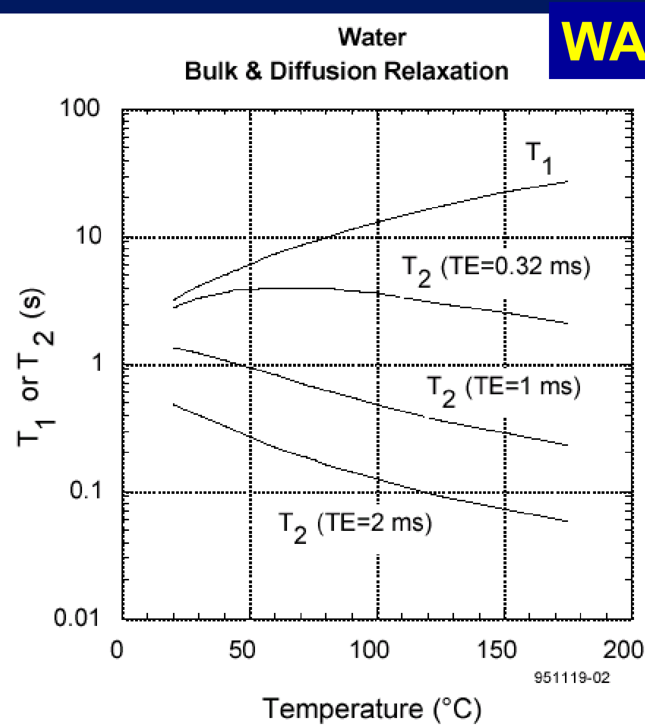
Vinegar, 1995



$$T_2^{-1} = R_2 = R_{2int} + R_{2diff}$$

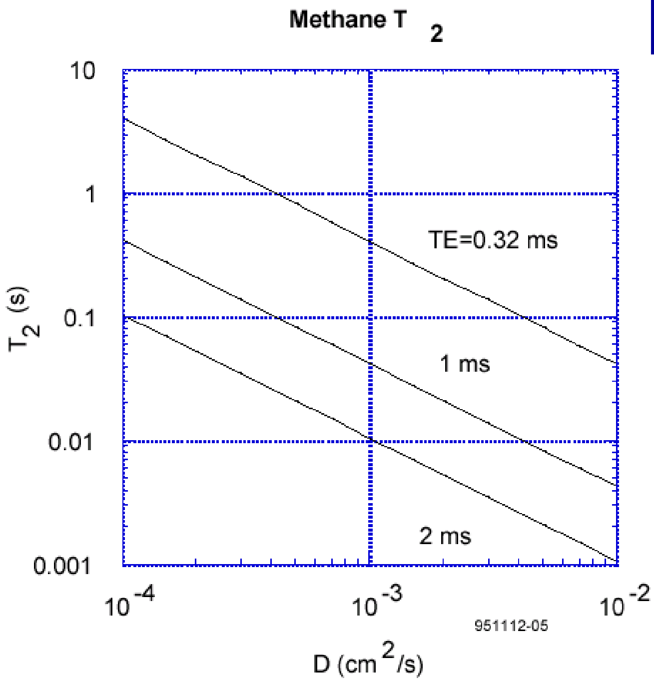
$$R_{2diff} = \frac{\gamma^2 G^2 TE^2 D}{12}$$

WATER RELAXATION



Tool Gradient: G = 20 Gauss/cm

GAS RELAXATION



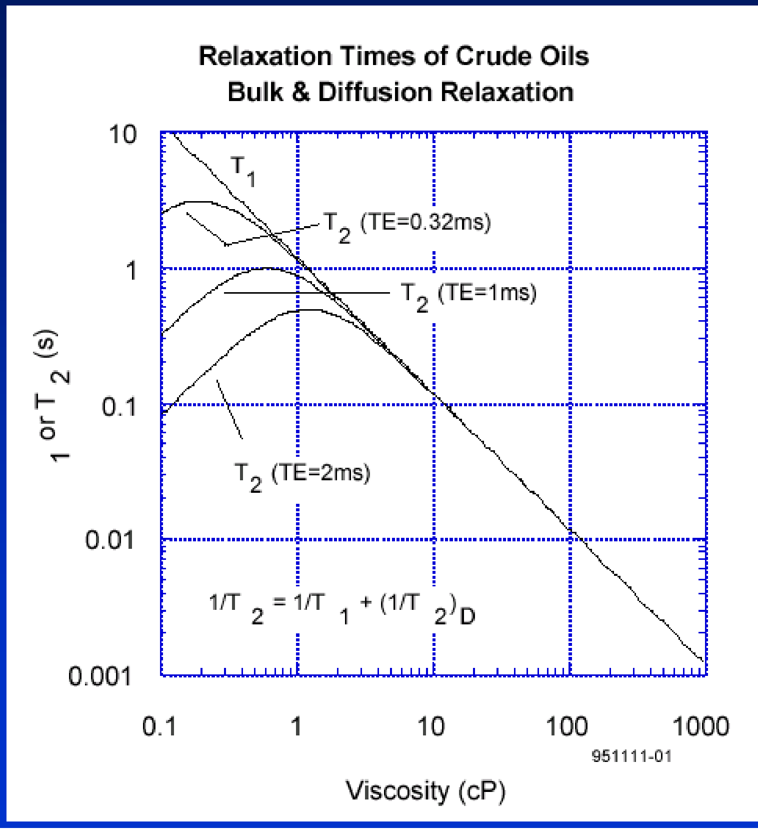
Tool Gradient: G = 20 Gauss/cm
Unrestricted Diffusion of Gas

SUMMARY: RELAXATION MECHANISMS

		T_1	T_2	T_1/T_2
Mineral Hydrogen		10-100 sec	10-100 μsec	~106
Water	Clastic	Surface Dominated	Surface Dominated	$T_1/T_2=\xi$ ξ~1.5
	Vugs	Bulk*	Bulk/ Diffusion*	$T_1 \geq T_2$
Oil	Medium to Heavy	Bulk*	Bulk*	$T_1=T_2$
	Light	Bulk*	Bulk/ Diffusion*	$T_1 \geq T_2$
Gas		Bulk*	Diffusion*	$T_1>>T_2$

(*) Independent of formation. Consult appropriate chart.

RELAXATION TIMES FOR CRUDE OILS



Elements of T2 Decay

(Wetting Phase Saturation = 100%)

Surface Relaxivity

Pore Surface Area to Volume Ratio

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

Bulk Fluid Relaxivity

Diffusion Decay

Primary Controls on T2 Decay

(Wetting Phase Saturation = 100%)

Pore Size & Geometry

Wettability

Pore Fluid Viscosity

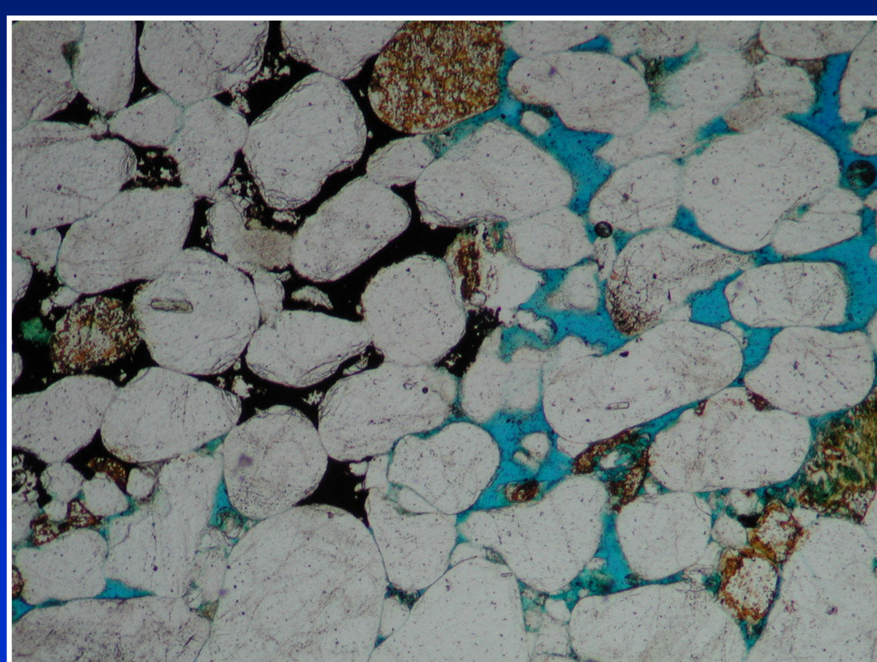
$$\frac{1}{T_2} = \rho \frac{S}{V} + \frac{1}{T_{2b}} + \frac{1}{T_{2D}}$$

Magnetics

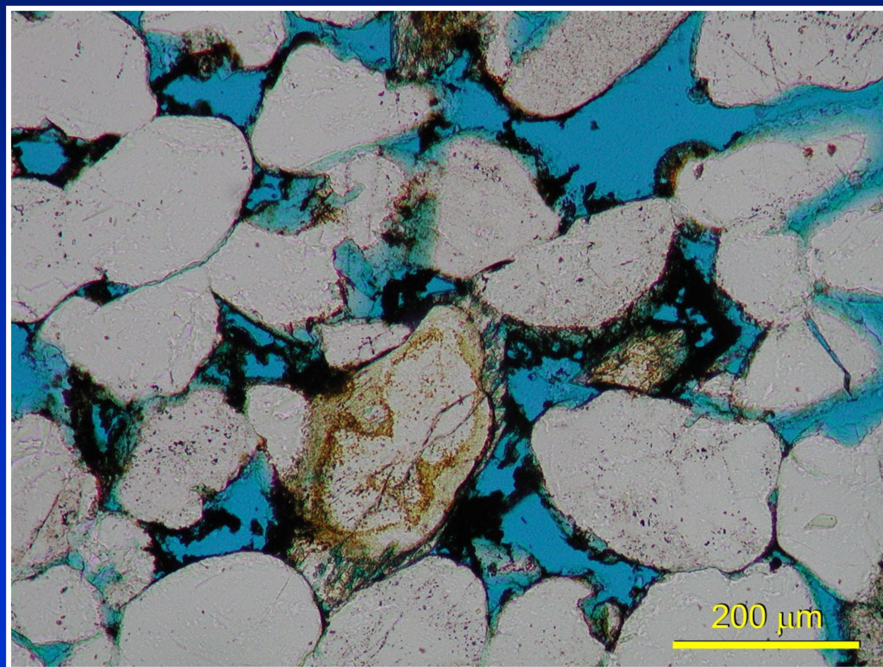
Pore Mineralogy

Pore Fluid Diffusivity
Magnetic Field Gradient
Inter-Echo Spacing (TE)

The Interplay between NMR Transverse Relaxation, NMR Gradient Diffusion, Pore Size Distribution, and Fluid Distribution



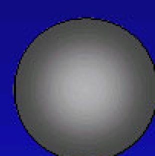
The Interplay between NMR Transverse Relaxation, NMR Gradient Diffusion, Pore Size Distribution, and Fluid Distribution



SURFACE-to-VOLUME RATIO

$$\frac{1}{T_2} \approx \rho \frac{S}{V} \propto \rho \frac{1}{length}$$

Sphere

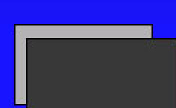


$$\frac{S}{V} = \frac{4\pi r^2}{\frac{4}{3}\pi r^3} = \frac{3}{r}$$

Cylinder

$$\frac{S}{V} = \frac{2\pi r h}{\pi r^2 h} = \frac{2}{r}$$

Fracture

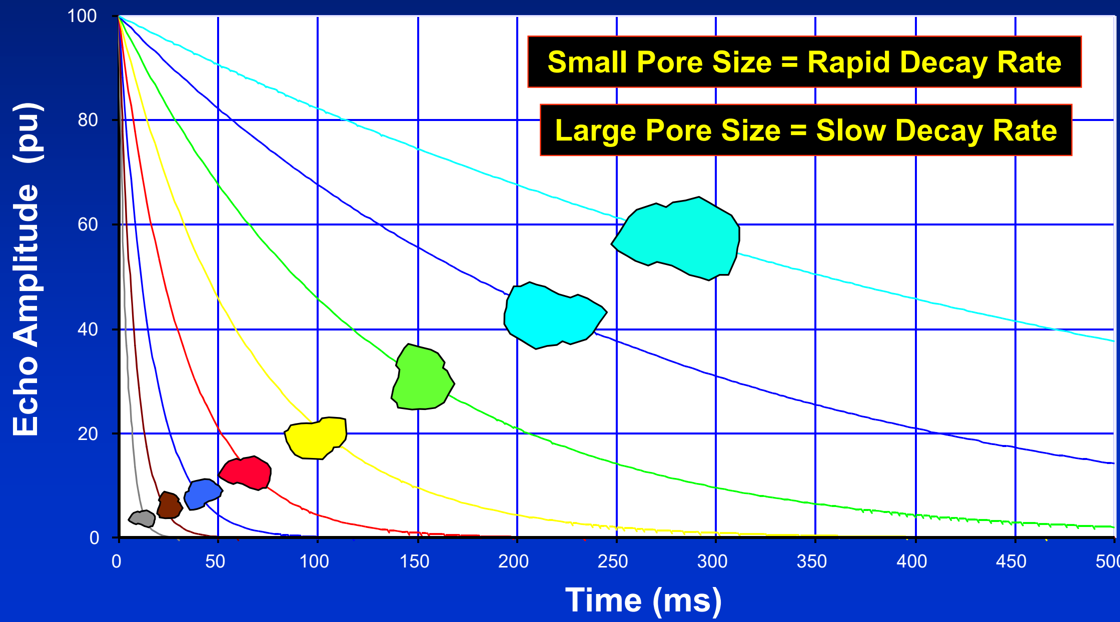


$$\frac{S}{V} = \frac{2Ah}{Ah\delta} = \frac{2}{\delta}$$

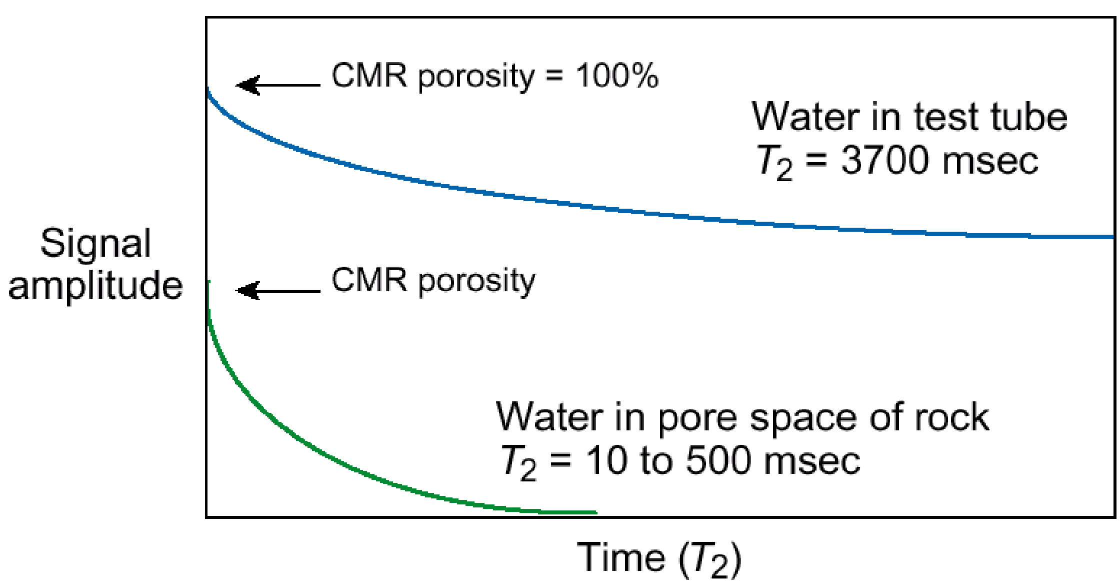
T_2 is proportional to pore size

T_2 Decay and Pore Size

(Wetting Phase Saturation = 100%)

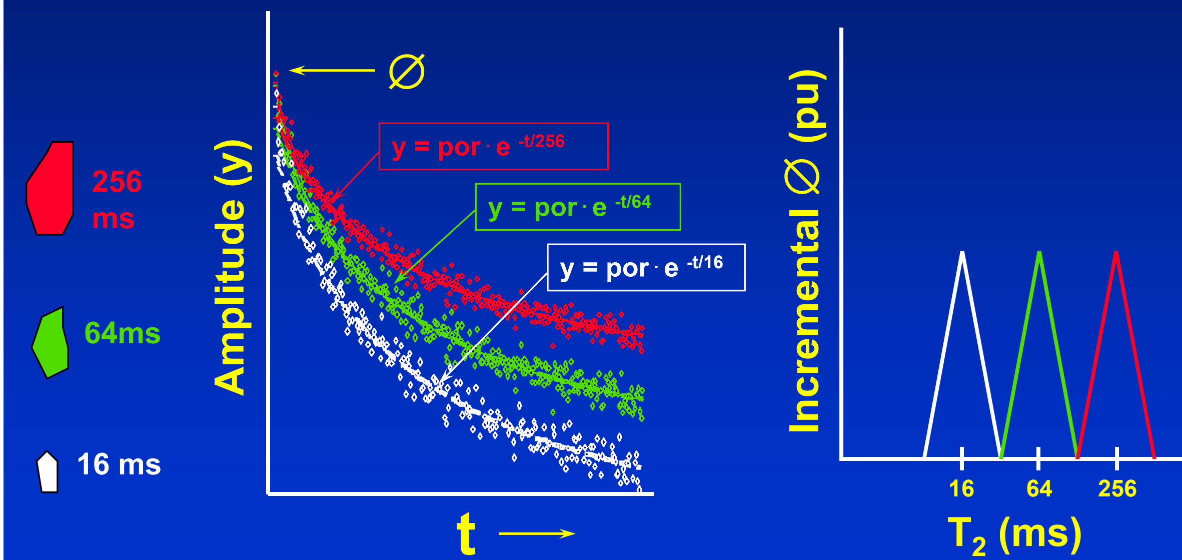


RELATIONSHIP WITH POROSITY, Quantification Procedure



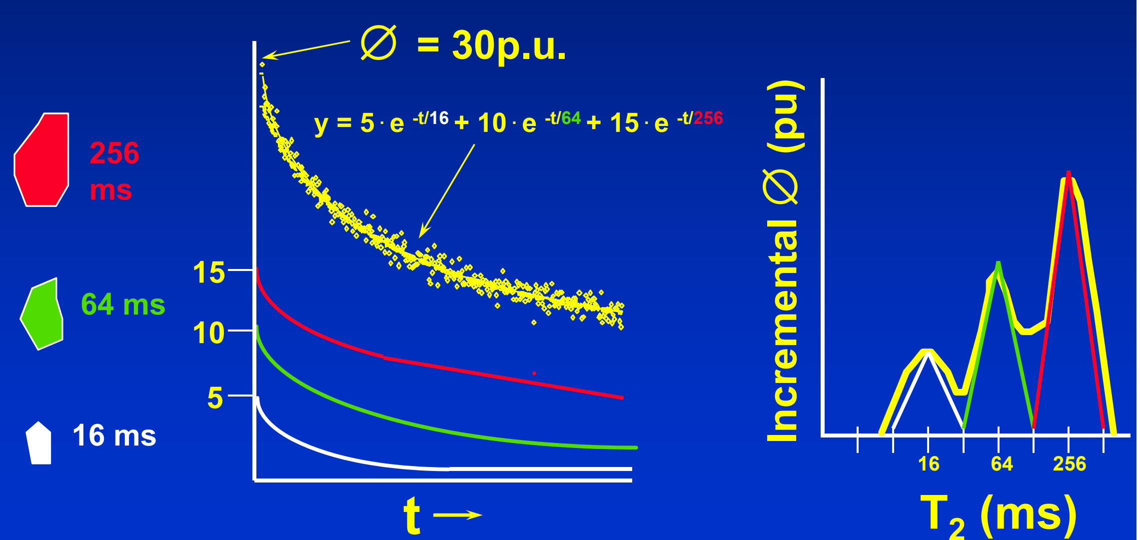
Single Exponential Decay

$$y = por \cdot e^{-t/T_2}$$

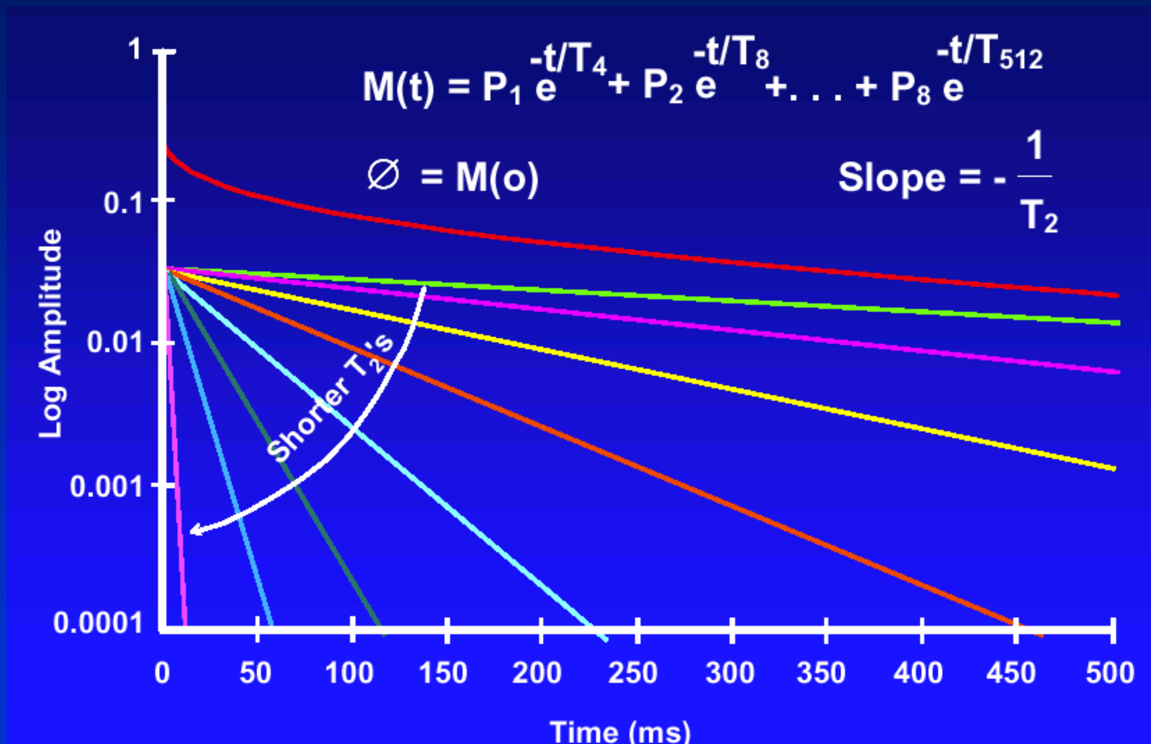


Multi-exponential Decay

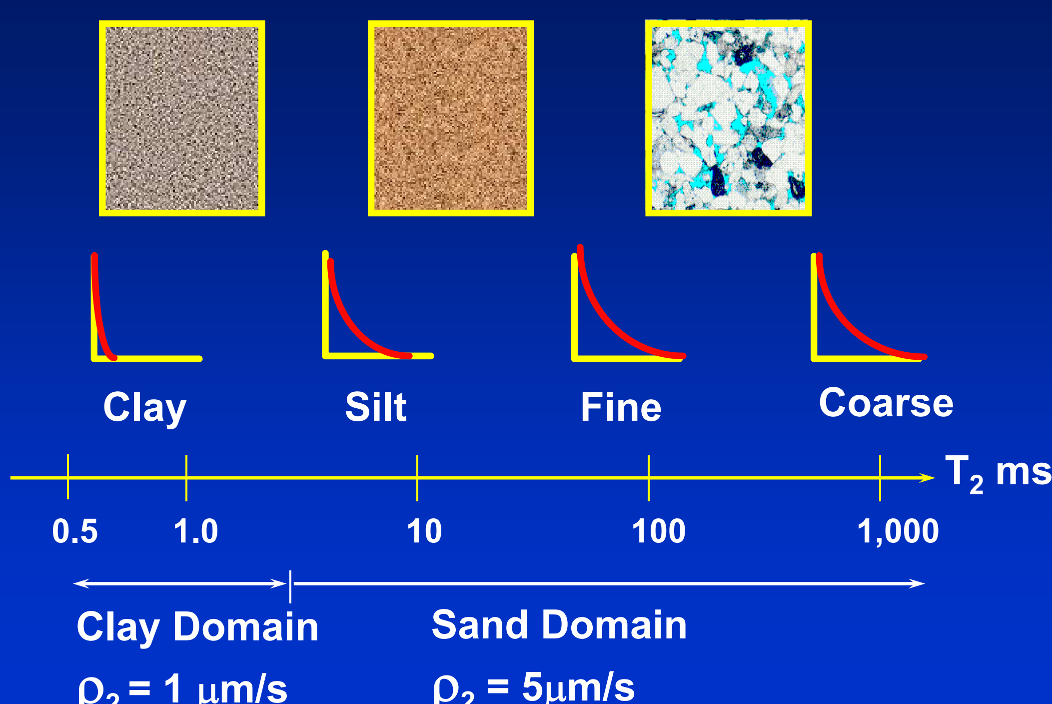
$$\varnothing = \Sigma\, por \cdot e^{-t/T_2}$$



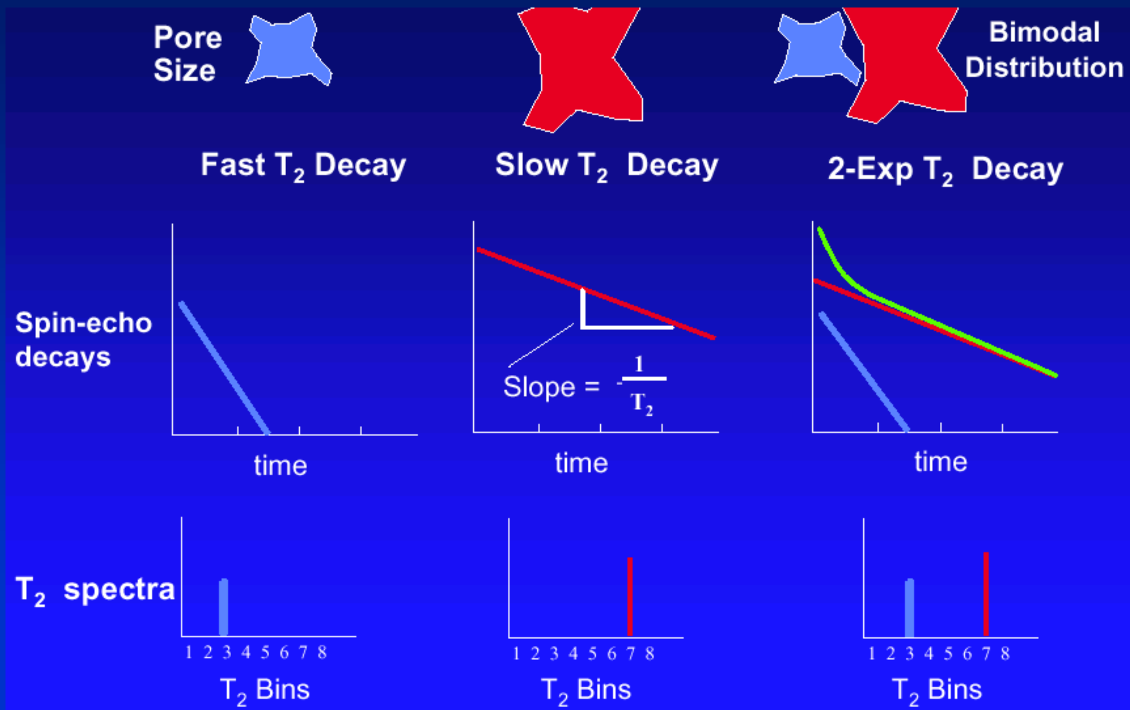
NMR DATA INVERSION: SUM OF EXPONENTIALS



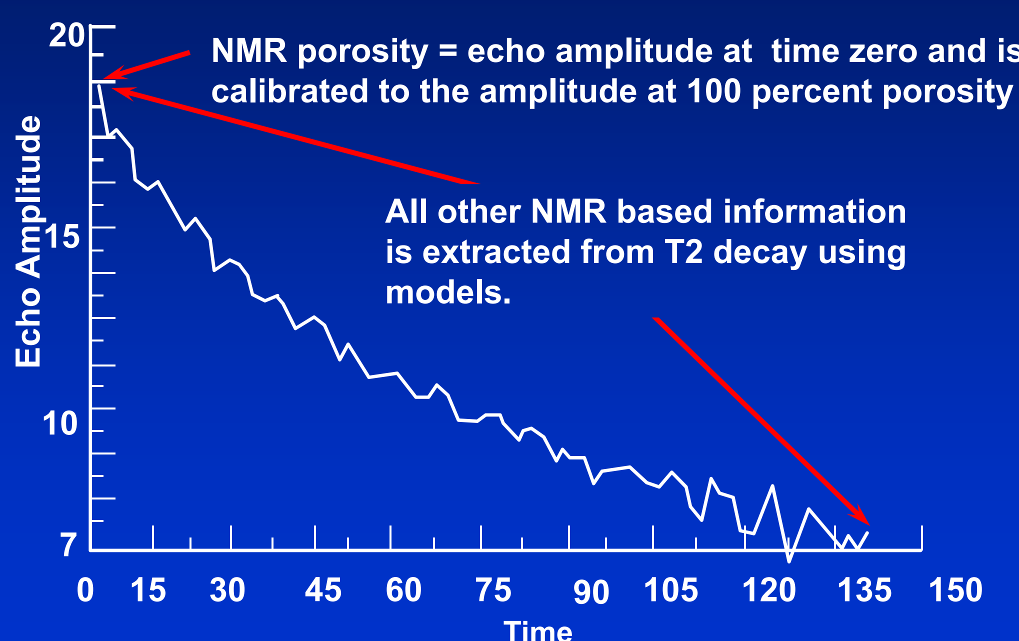
T2 RELAXATION AND PORE SIZE



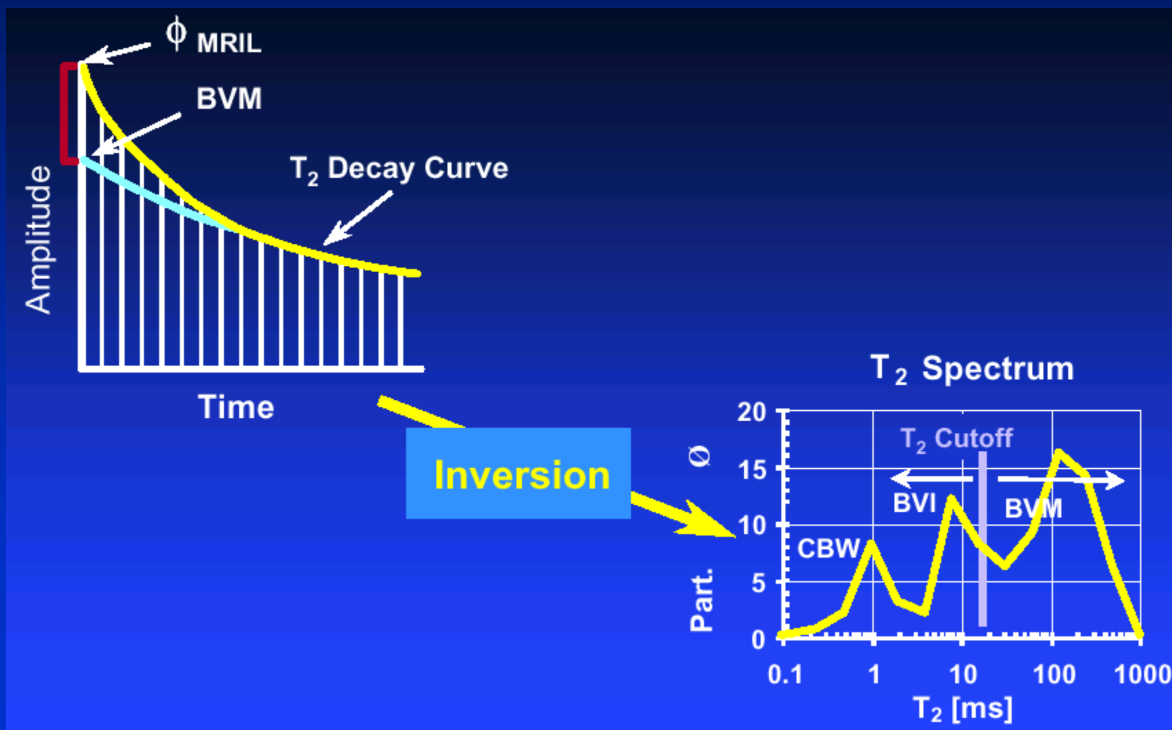
T2 RELAXATION AND PORE SIZES



TOTAL POROSITY vs. FRACTIONAL POROSITY



INVERSION OF ECHO DATA



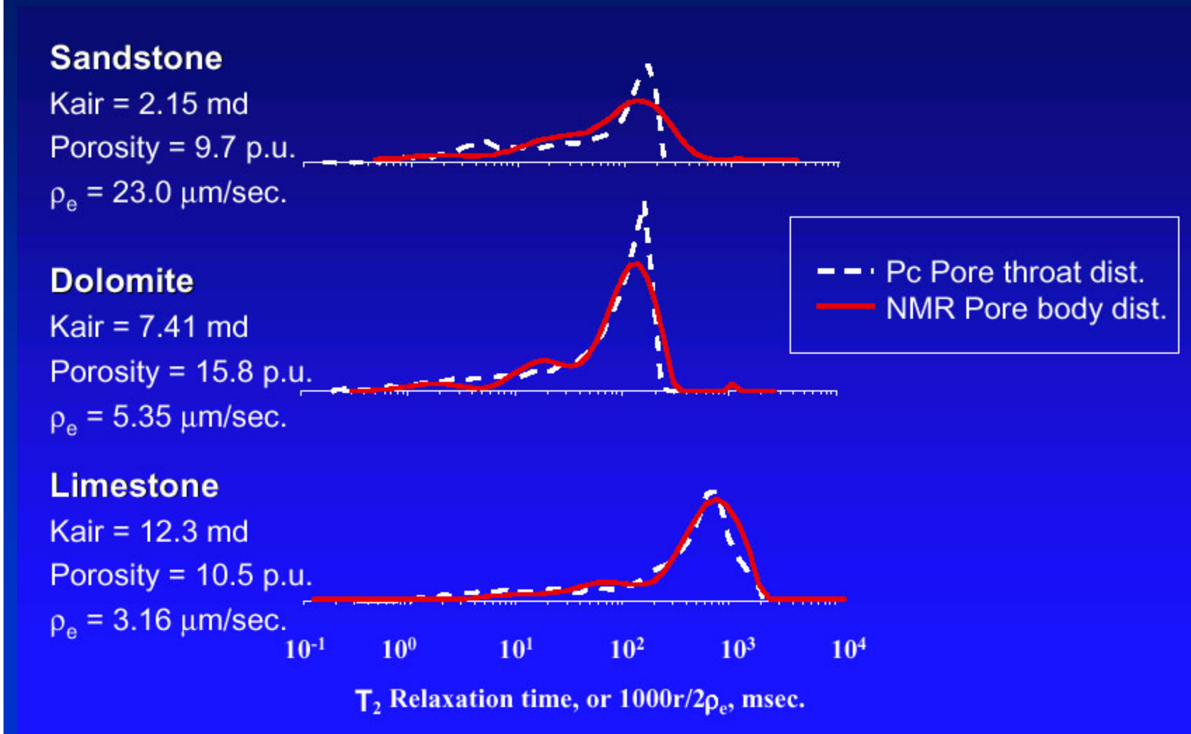
SPECIFIC SURFACE AREA FOR COMMON ROCK TYPES

Material		[m2/g]
Pure Quartz Crystals		0.15•10-4
Quartz Spheres	60 µm	0.025
	30 µm	0.05
	2 µm	0.75
	1 µm	1.5
Crushed Quartz		3.1
Kaolinite		10- 40
Illite		30 - 70
Smectite		550 - 750
Limestone (Trenton & Caddo Form)		0.1 - 0.35
Gulf Coast Shaly Sands (Vc ~ 15 - 30%)		100 - 450

Source of Data

Zemanek, 1989
Carman, 1956
Brooks and Purcell, 1952
Almon and Davies, 1978

COMPARISON OF DISTRIBUTIONS

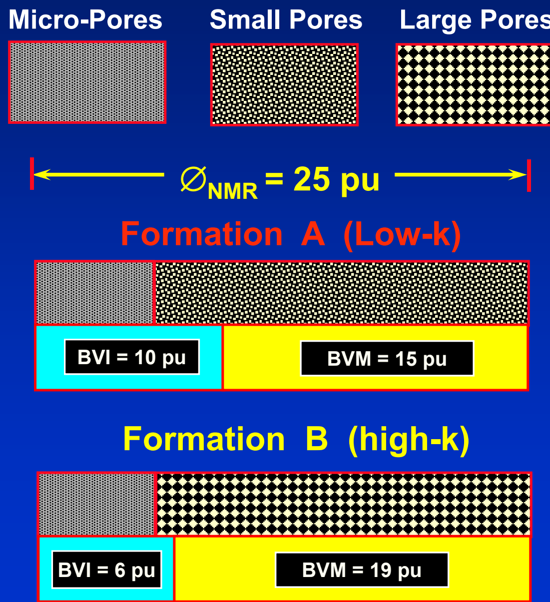


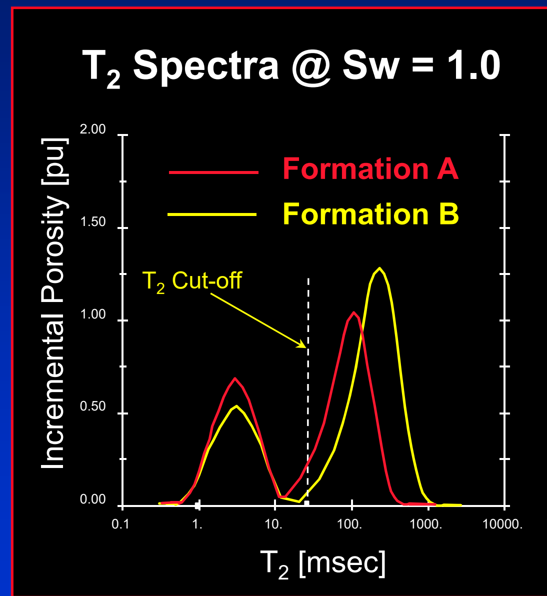
NMR PROPERTIES: CLAY MINERALS

Clay mineral	Specif. Internal Surface m^2/g	Cation Exchange Capacity CEC meq/100g	T_2 ms
Montmorillonite	760	76	0.3 … 1
Illite	93	15	1 … 2
Kaolinite	18	4	8 … 16

Effect of Pore Size on T2 Spectra

(Wetting Phase Saturation = 100%)





Surface Relaxivity and T_2 Decay

Controls on Surface Relaxivity ρ

- **Pore surface mineralogy**
- **Para, ferri, and ferro-magnetic ions (e.g., Fe^{3+}, Mn^{2+})**
- **Wettability**

Effects of ρ Variations (Wetting Phase Only)

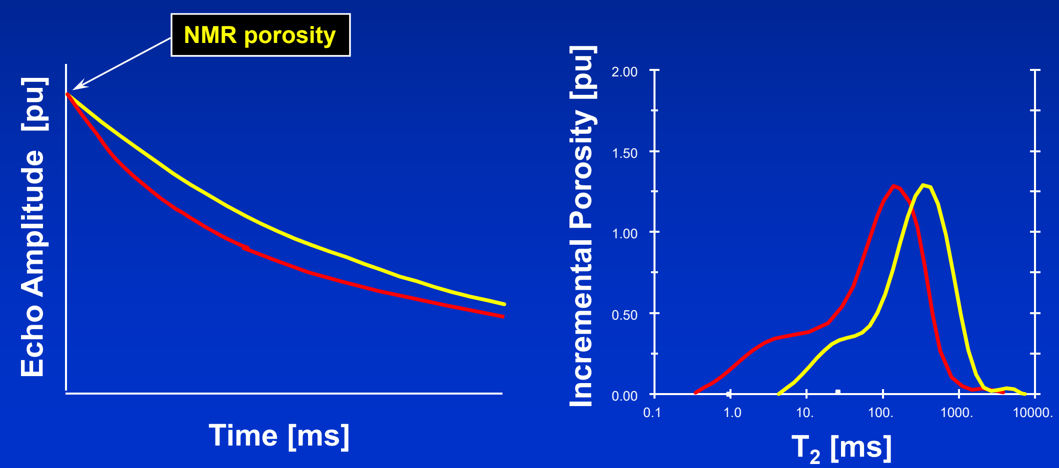
- **Higher ρ results in faster T_2 Decay**
- **Lower ρ results in slower T_2 Decay**

Surface Relaxivity and T_2 Decay

(Wetting Phase Saturation = 100%)

Low ρ (Carbonates)

High ρ (Clastics)

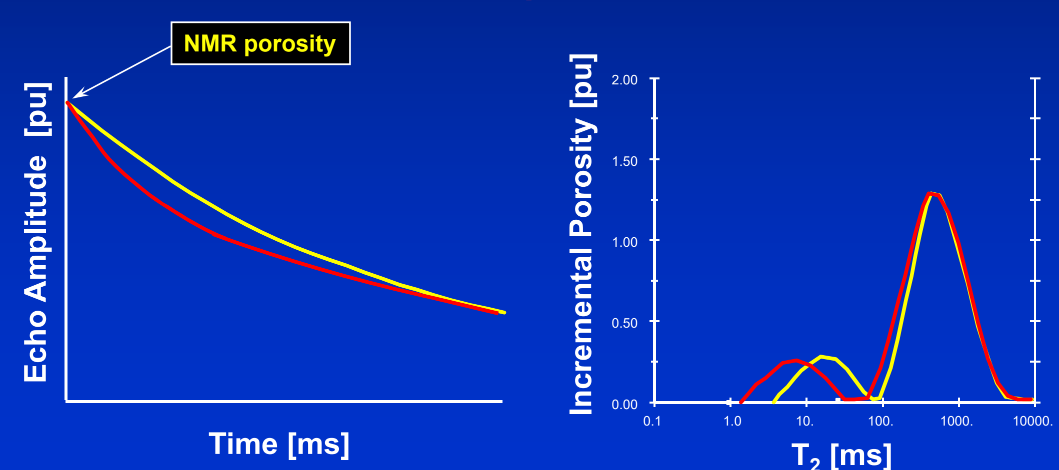


Surface Relaxivity and T_2 Decay

2-phase Fluid System, Wetting Phase @ Irreducible Saturation

Low ρ (Carbonates)

High ρ (Clastics)

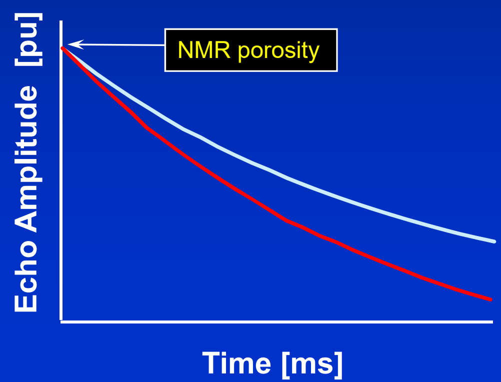


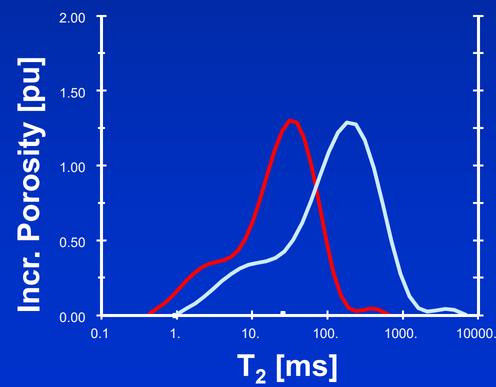
Effect of Magnetic Ions on T_2 Decay

The presence of Para, ferri, and ferro-magnetic ions (e.g., Fe^{3+}, Mn^{2+}) will increase ρ and produce internal magnetic field gradients which attenuate echo amplitudes due to accelerated diffusion decay (T_{2D}).

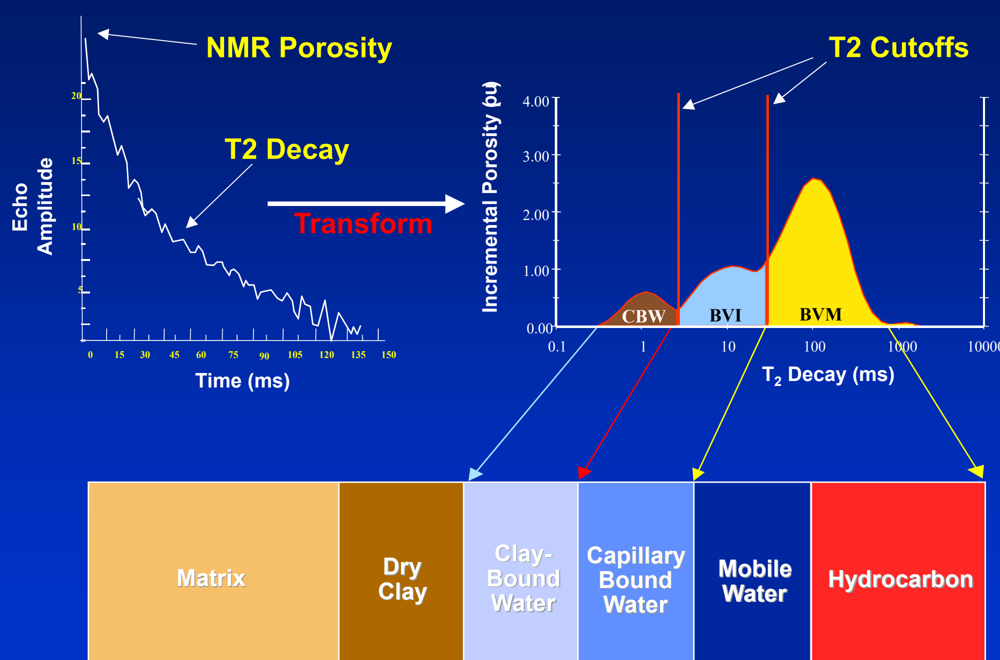
Mineral Constituents with Low Magnetic Susceptibility

Mineral Constituents with High Magnetic Susceptibility

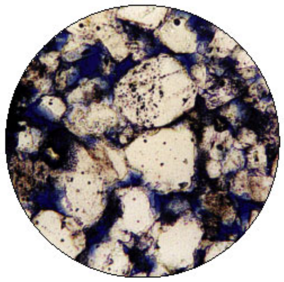




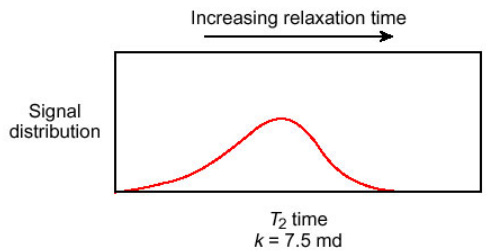
Pore Volumetric Distribution

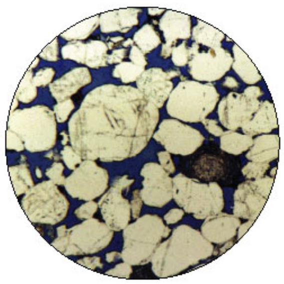


WILL THE WELL PRODUCE?

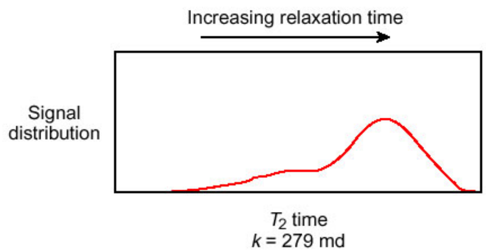


Porosity = 20%
Permeability = 7.5 md

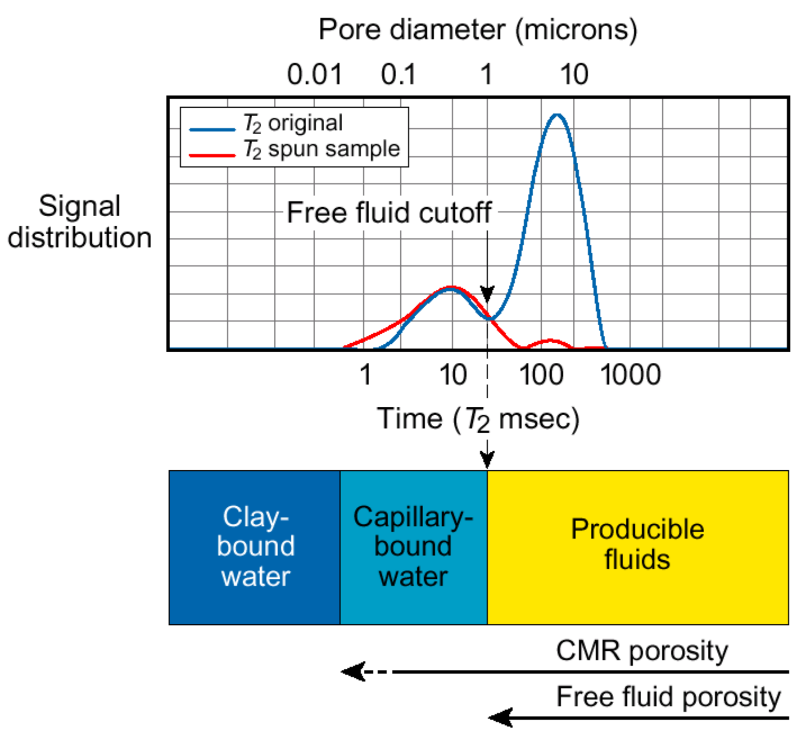




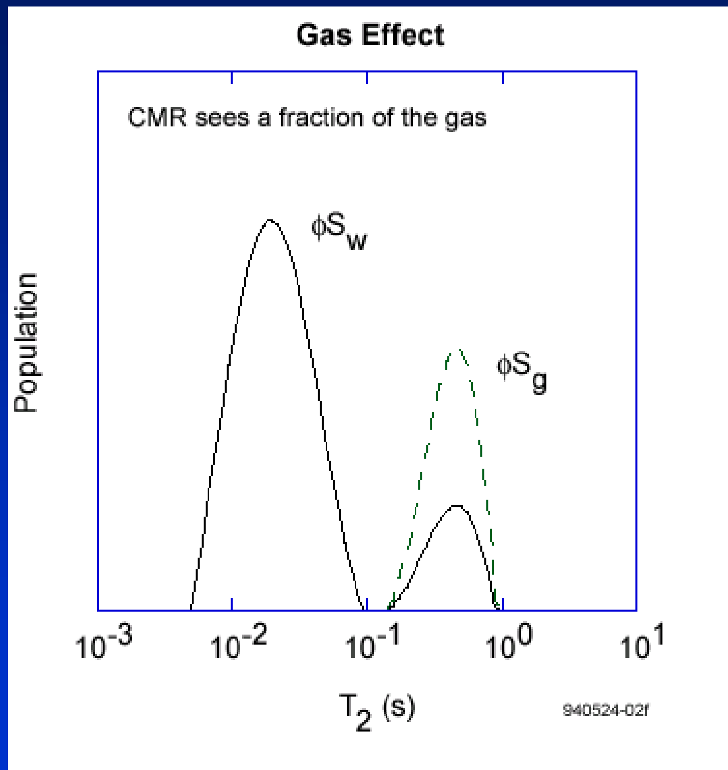
Porosity = 19.5%
Permeability = 279 md



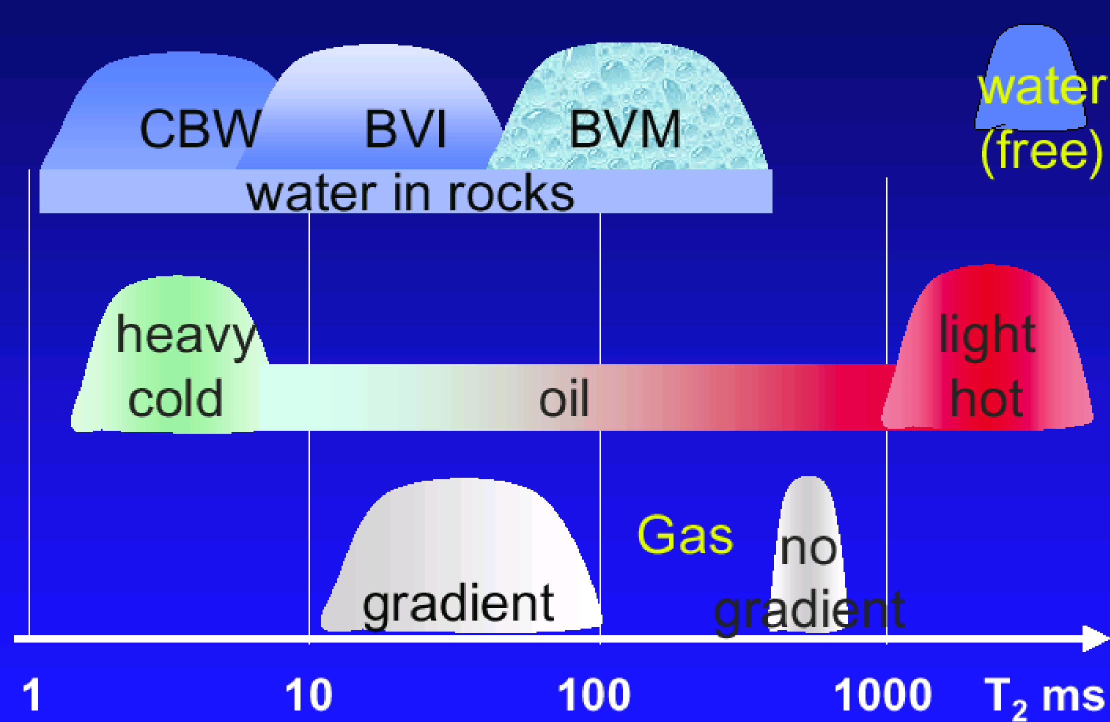
FREE FLUID vs. IRREDUCIBLE FLUID



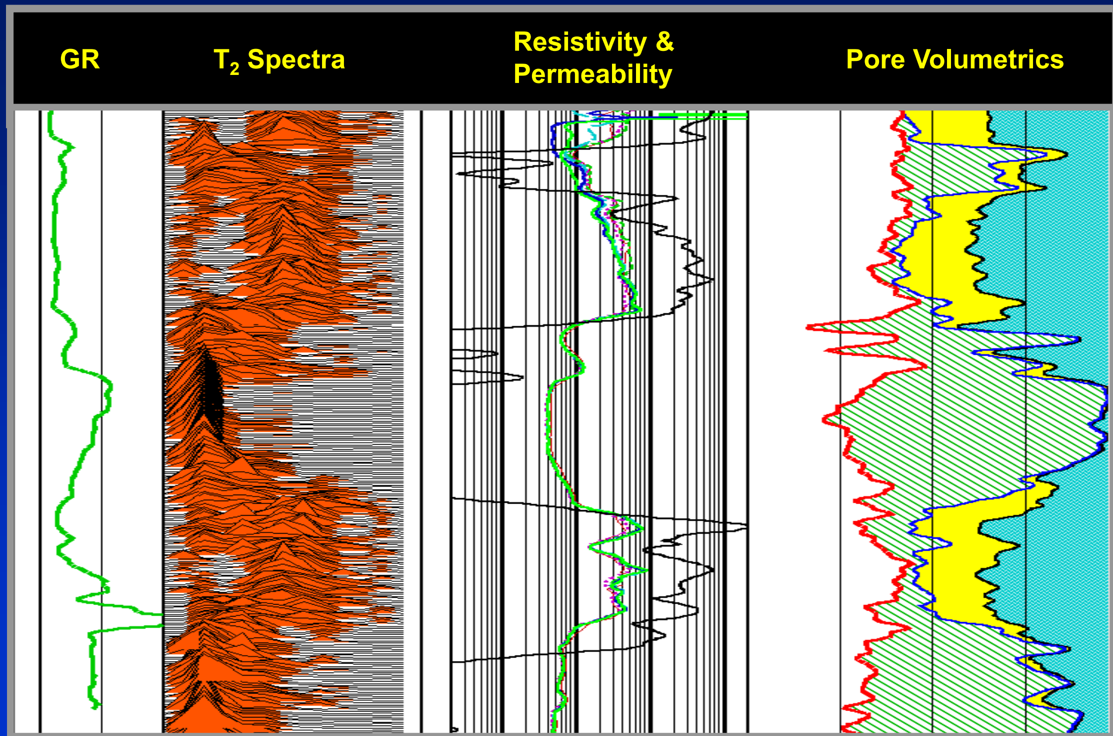
GAS EFFECT

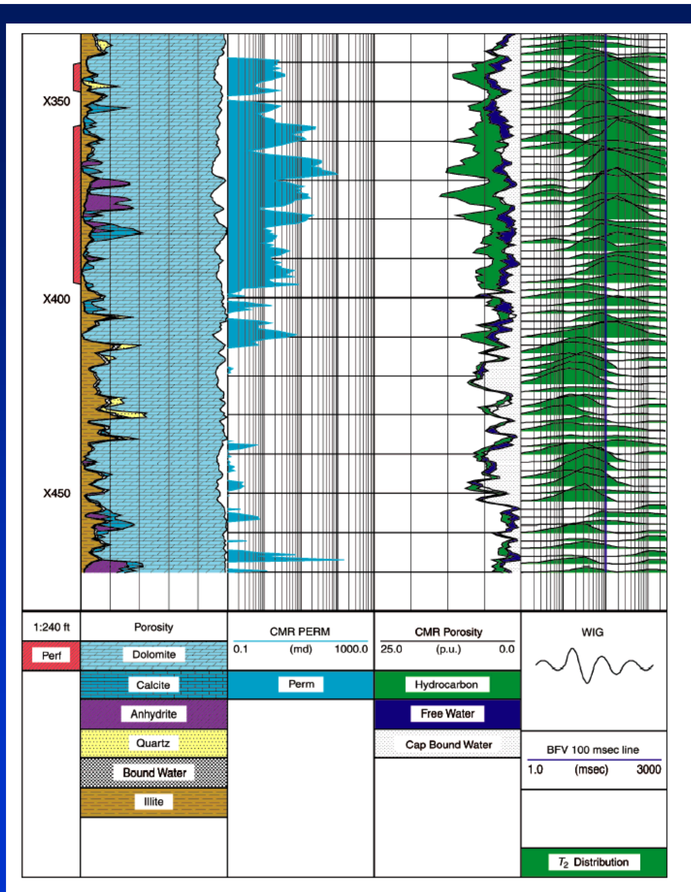


NMR TRANSVERSE RELAXATION: An Overview



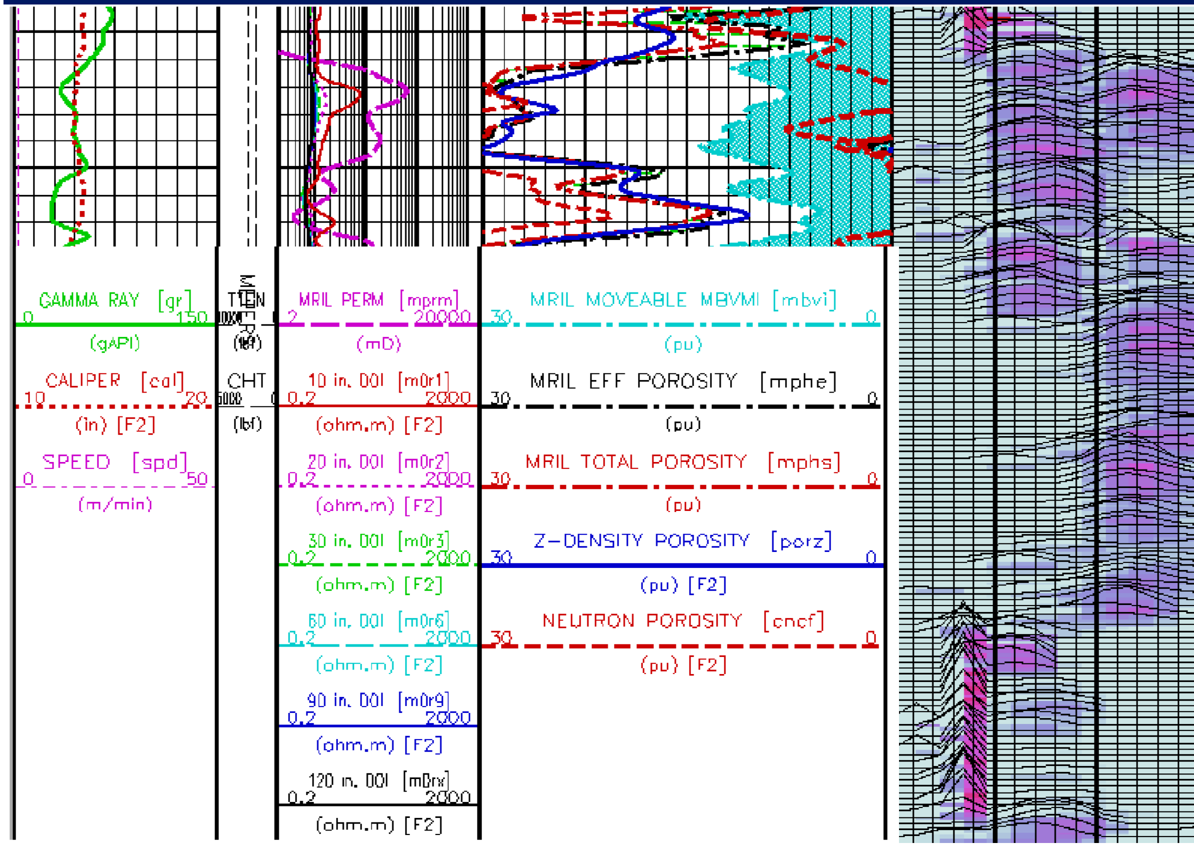
Basic NMR Field Deliverable



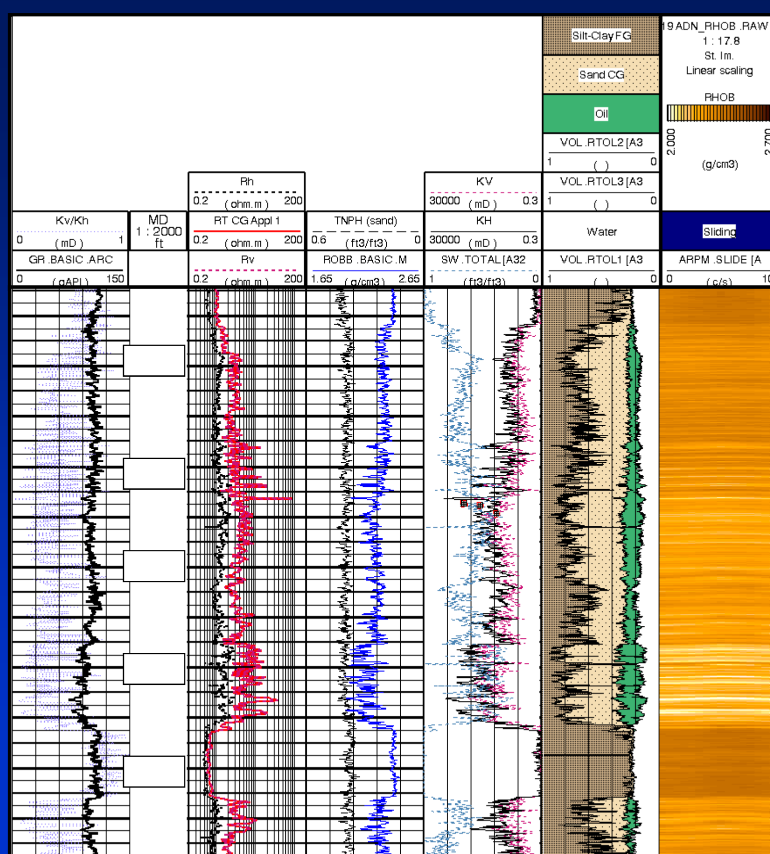


EXAMPLE: PRODUCIBILITY ANALYSIS

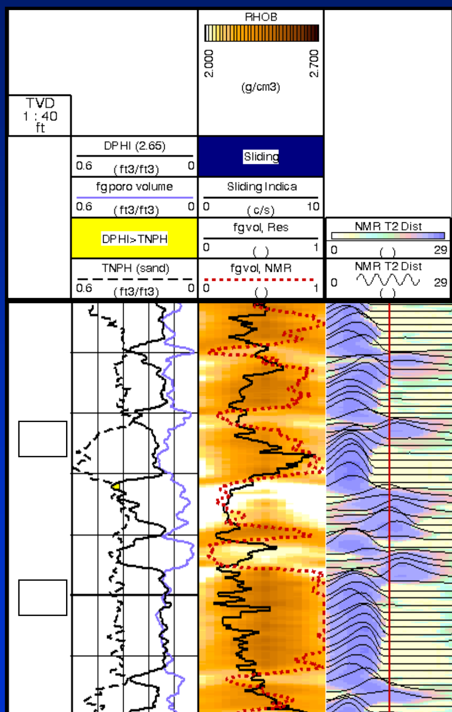
FIELD LOG EXAMPLE

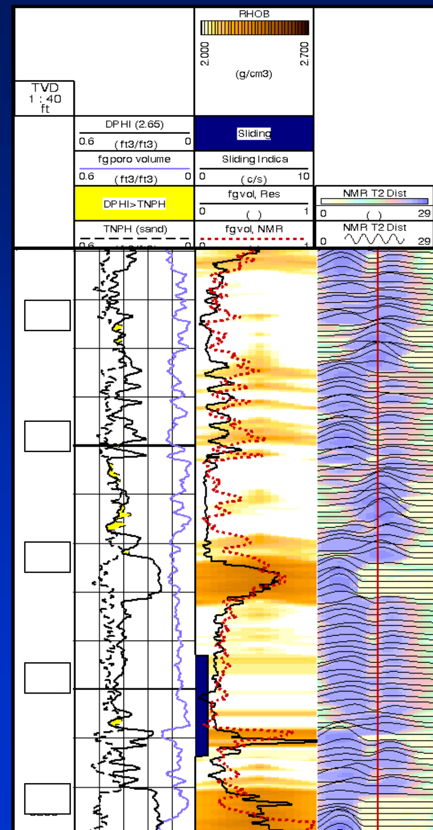


THIN, LAMINATED-BED ANALYSIS

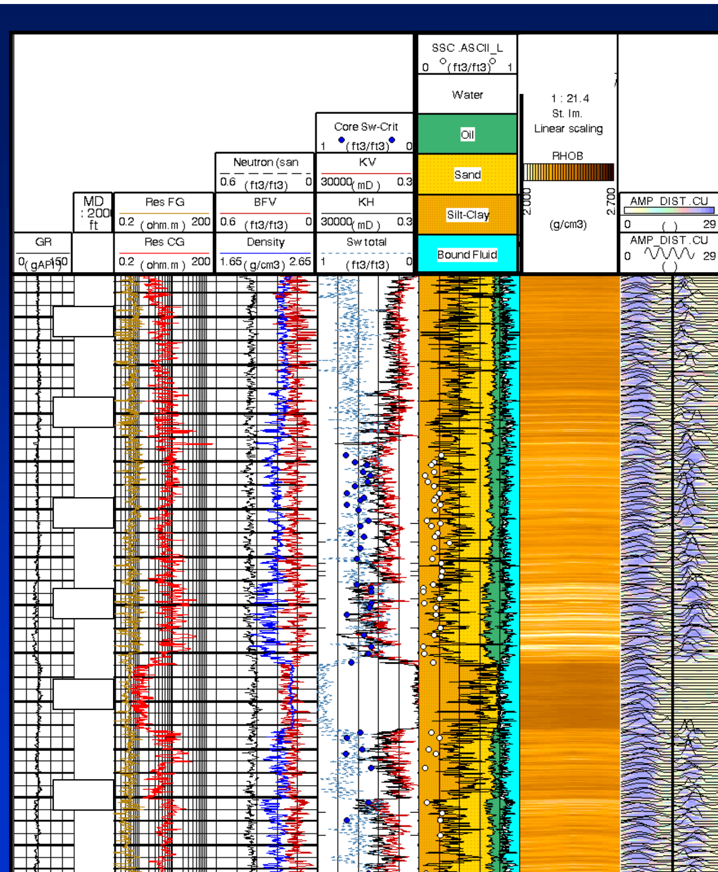


THIN, LAMINATED-BED ANALYSIS

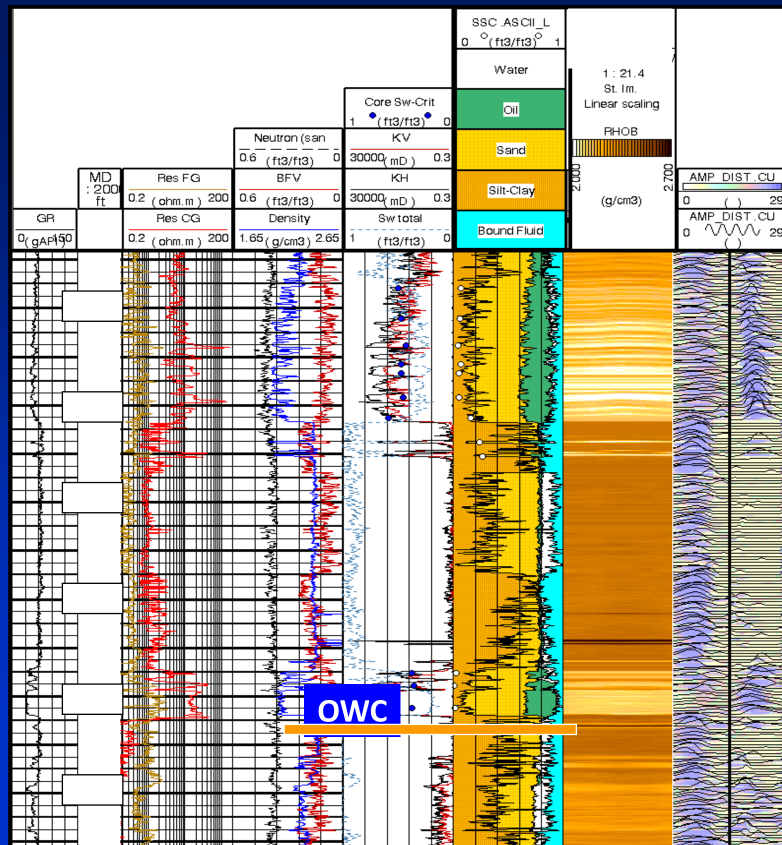




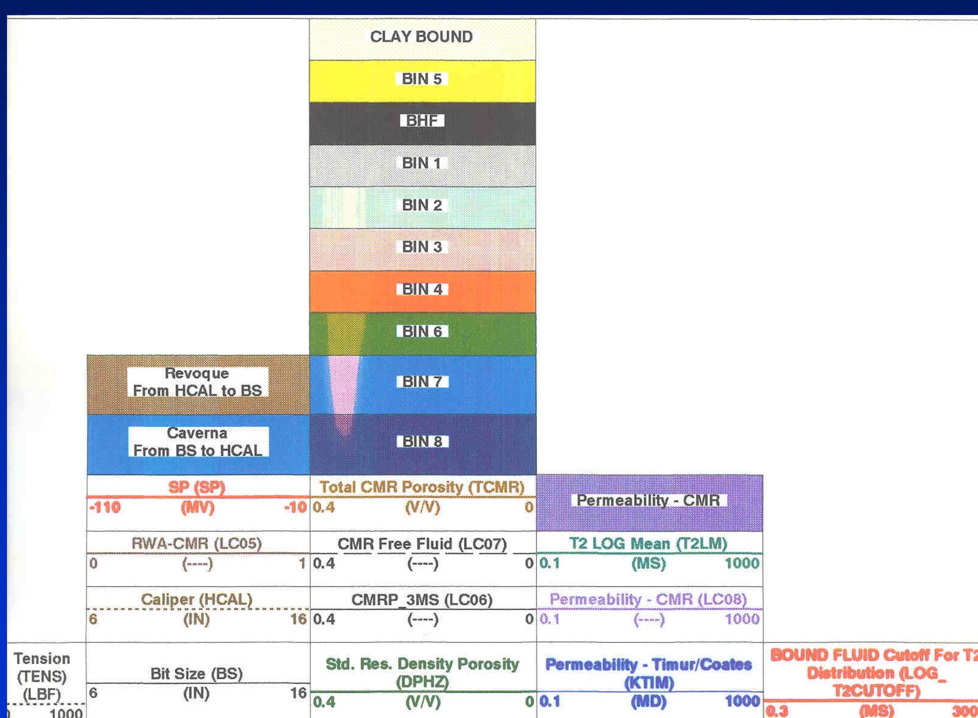
THIN, LAMINATED-BED ANALYSIS



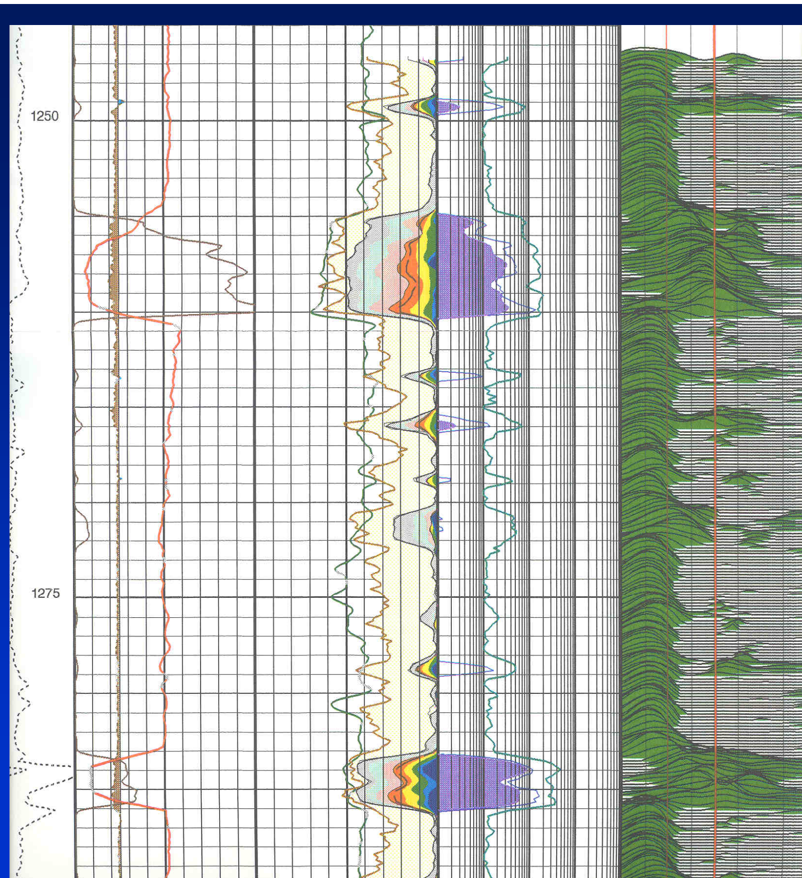
THIN, LAMINATED-BED ANALYSIS



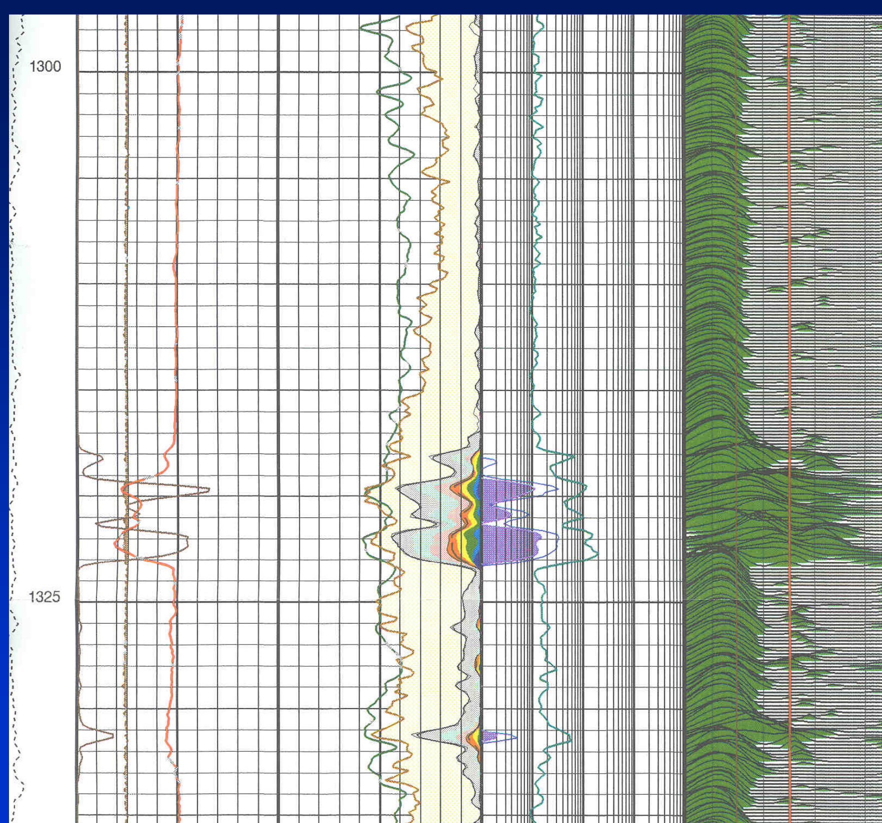
Patagonia Example

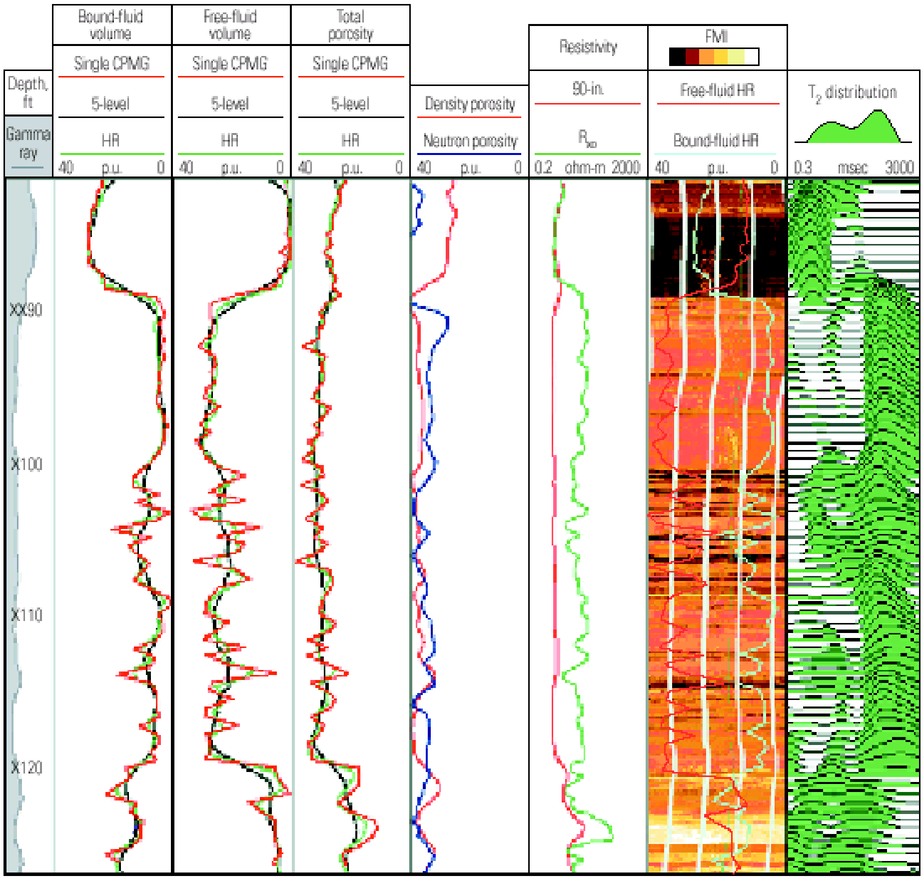


Patagonia Example



Patagonia Example



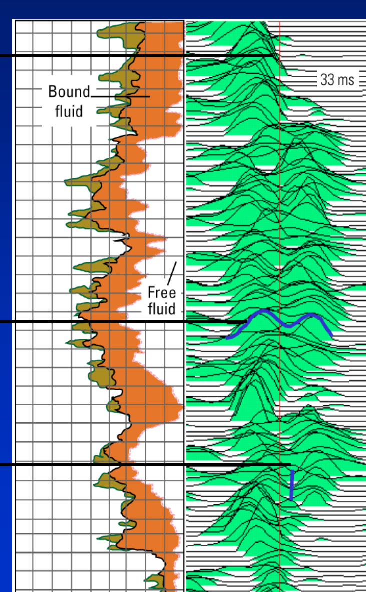


NMR T2 Distributions

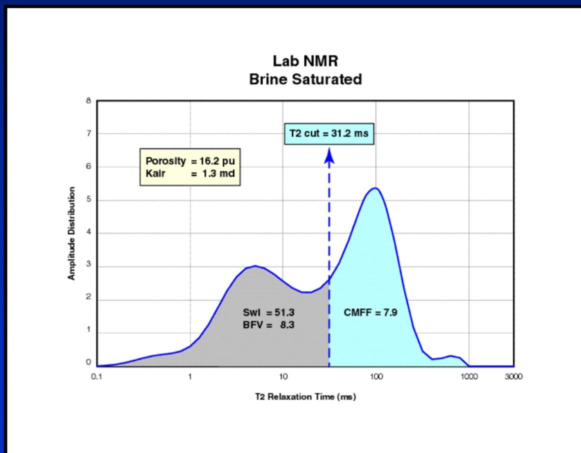
Typically, use a 33-ms cutoff for T_2 in sandstone.

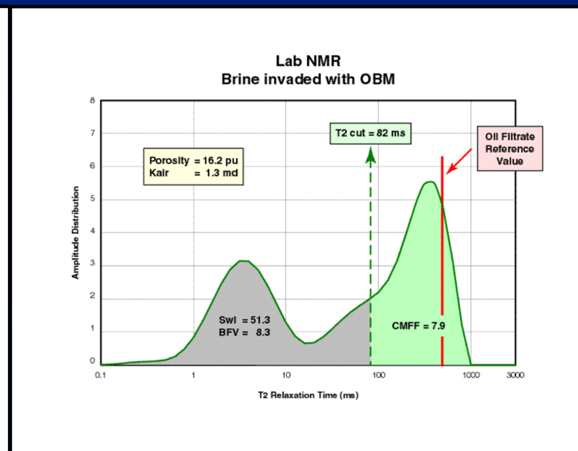
T_2 distributions show a distinct bimodal distribution characteristic of bulk relaxation of the oil-based mud filtrate invasion.

The 33-ms line on the T_2 distribution is below valley separating bulk free fluid from free fluid volume.



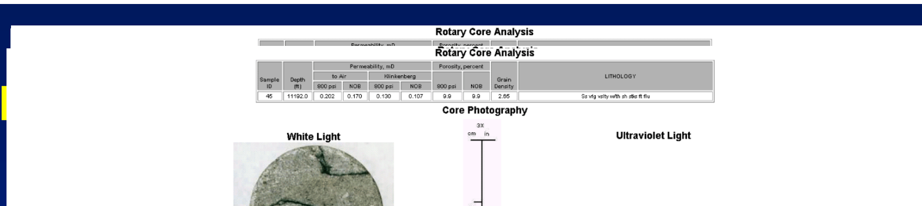
Influence of OBM Filtrate

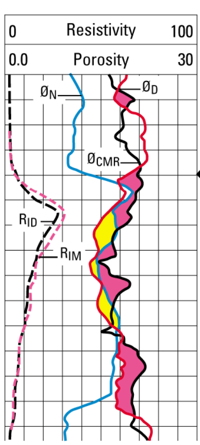


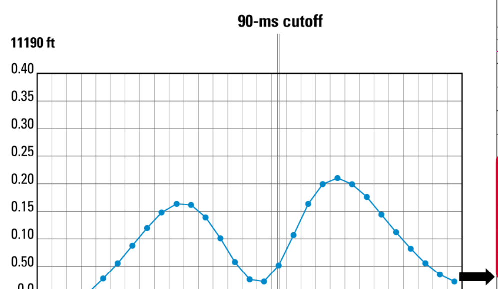


NI

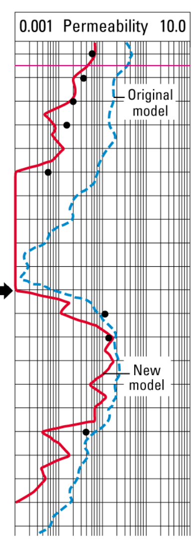
by



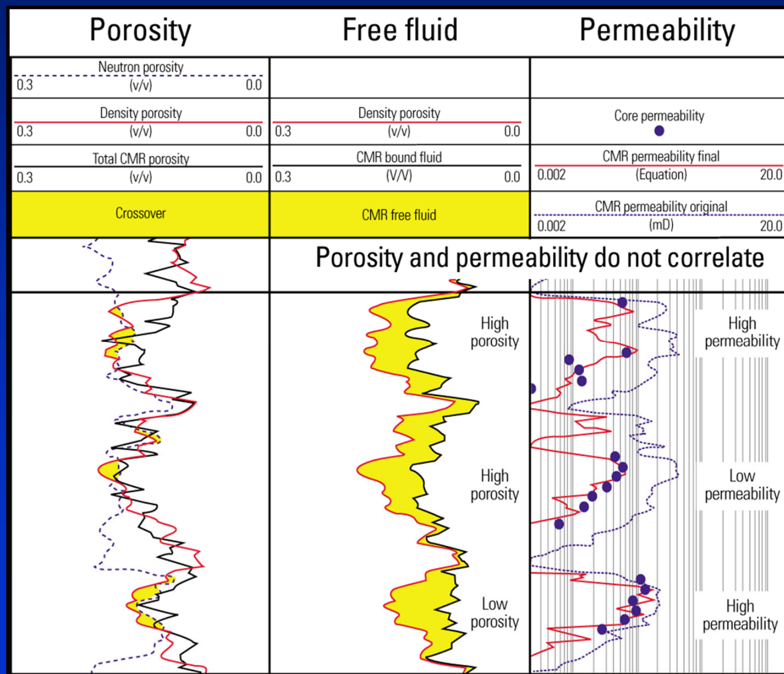




PHIE	PHI–CORE	DEPTH	KCMR	K–CORE
0.1153	9.90	11192	0.0094	0.1070
0.1355		11193	0.0679	
0.1421	11.30	11194	0.1578	0.1150
0.1431		11195	0.1068	
0.1485	12.40	11196	0.1628	0.0860
0.1561		11197	0.0993	
0.1508	11.60	11198	0.0457	0.0870
0.1421		11199	0.1136	
0.1365	10.60	11200	0.0582	0.0630
0.1285		11201	0.0595	
0.1127	10.40	11202	0.0039	0.0290
0.1127	10.40	11202	0.0039	0.0290



Results: Improved Permeability Transform



SUMMARY: HYDROCARBON EFFECTS ON NMR

In a water wet rock that contains hydrocarbons :

- The T2 distribution does not contain pore size information. However, the MBVI may still be correct.
- T2 geometric mean-based permeability estimation does not work.
- MBVM/MBVI-based permeability estimation works when logs are corrected for hydrocarbon effects.

SUMMARY: HYDROCARBON EFFECTS ON NMR

Fluid Type	HI	T1	T_2 component
light to moderate viscosity oil (<40 cp)	≈1	long	MBVM
heavy oil	≈1	short	→ MBVI
gas	<1	long	MBVM or MBVI*

* depends on tool frequency and environmental conditions

SUMMARY: FORMATION AND FLUID EFFECTS

Clay	Reduces MPHE-bound water relaxes too fast to detect with standard T2, can be measured with C/TP.
Gas	Low HI reduces MPHE; long T_1 but short T_2 due to diffusion
Light oil	Long T_1 increases TW, reduces logging speed; complicates application of mean type permeability models.
Heavy oil	Fast T_2 decay of oil signal complicates MBVM/MBVI interpretation.
Thin beds	Thin beds are not resolved. However, the volumetric porosity and permeability are still correct.

SUMMARY: ENVIRONMENTAL EFFECTS

Temperature	Reduces depth-of-investigation
Conductive mud	High Q loading reduces SNR, (logging speed); Interference signal from sodium
Washout > D_{MRIL}	MPHI too high, excess (mud) signal, usually in MBVI
Invasion	Alters native fluid saturations; primarily measures the flushed zone

SUMMARY:

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)**

Acknowledgements:

Baker Atlas
Schlumberger
Halliburton