Lateral-Motion Correction of NMR Logging-While-Drilling Data

(SPWLA-2018-LLL)

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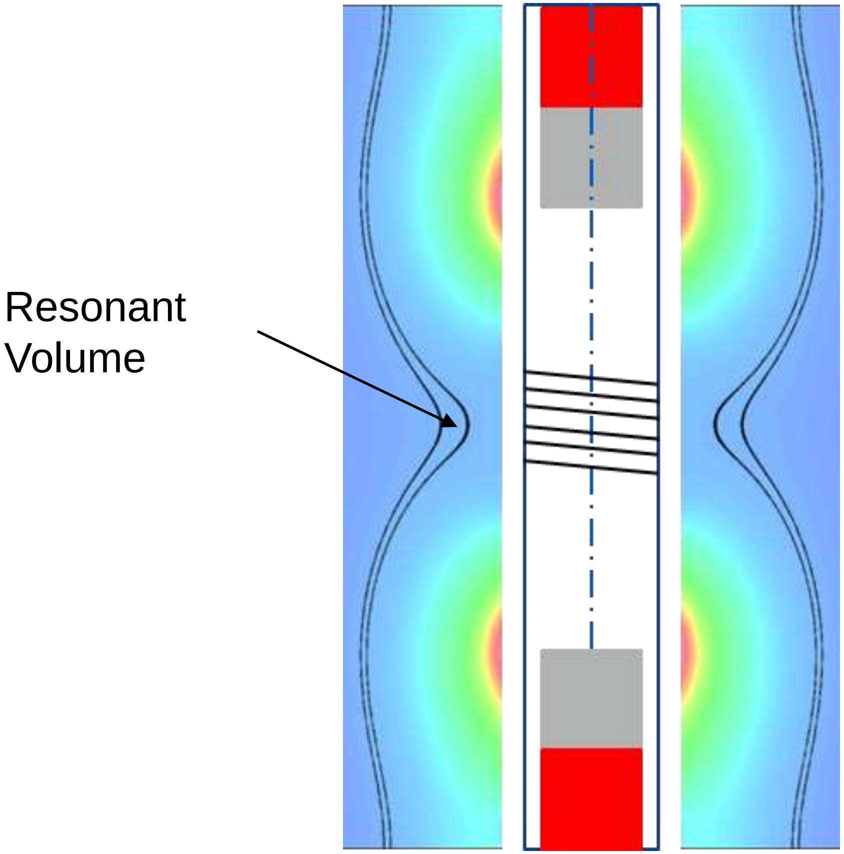
Outlook

- NMR motion effect → NMR flow effect
  - ROP motion flow effect
  - Lateral-motion flow effect
- Lateral-motion correction
- Data examples

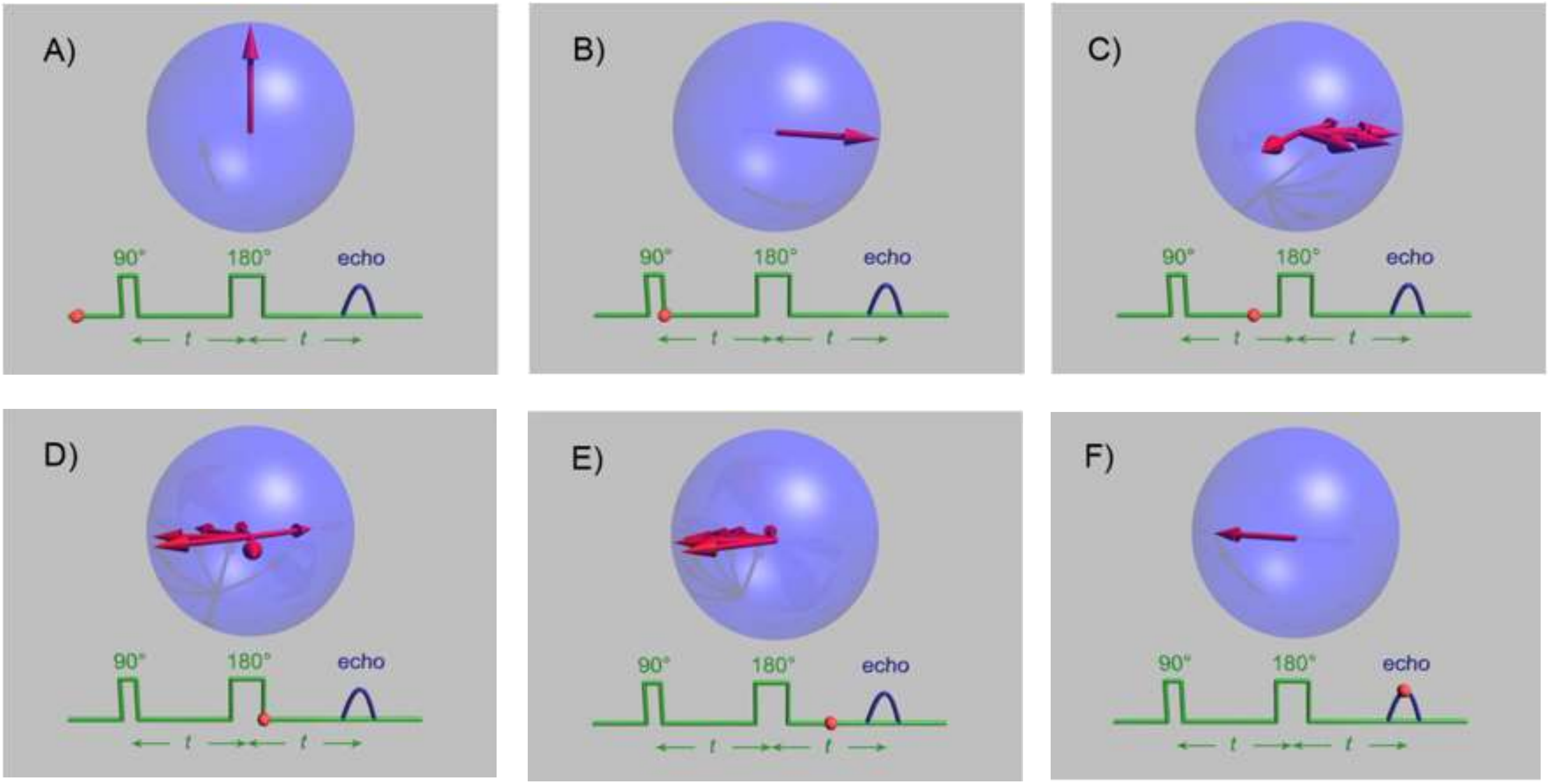
NMR MOTION EFFECT

MagTrak™ Tool & B_0 Field



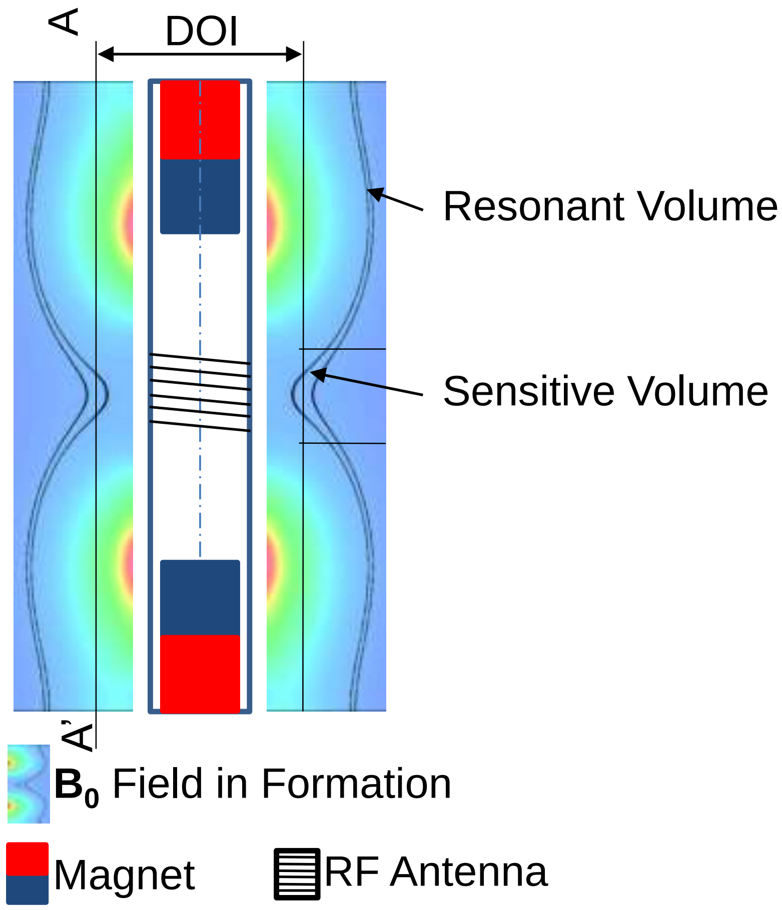
Coman et al., 2015, **SPE175050**

CPMG Pulse Sequence

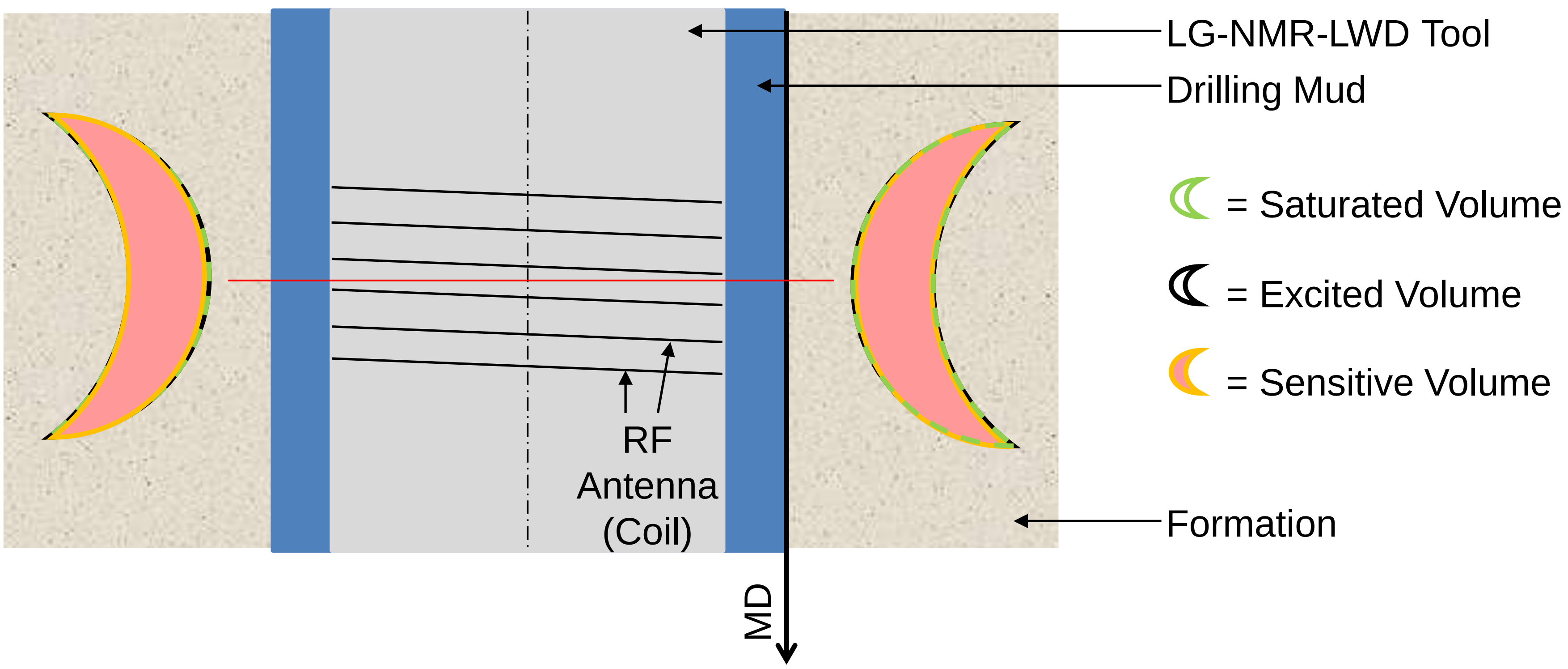


https://en.wikipedia.org/wiki/Spin_echo

Sensitive Volume & Contribution Map

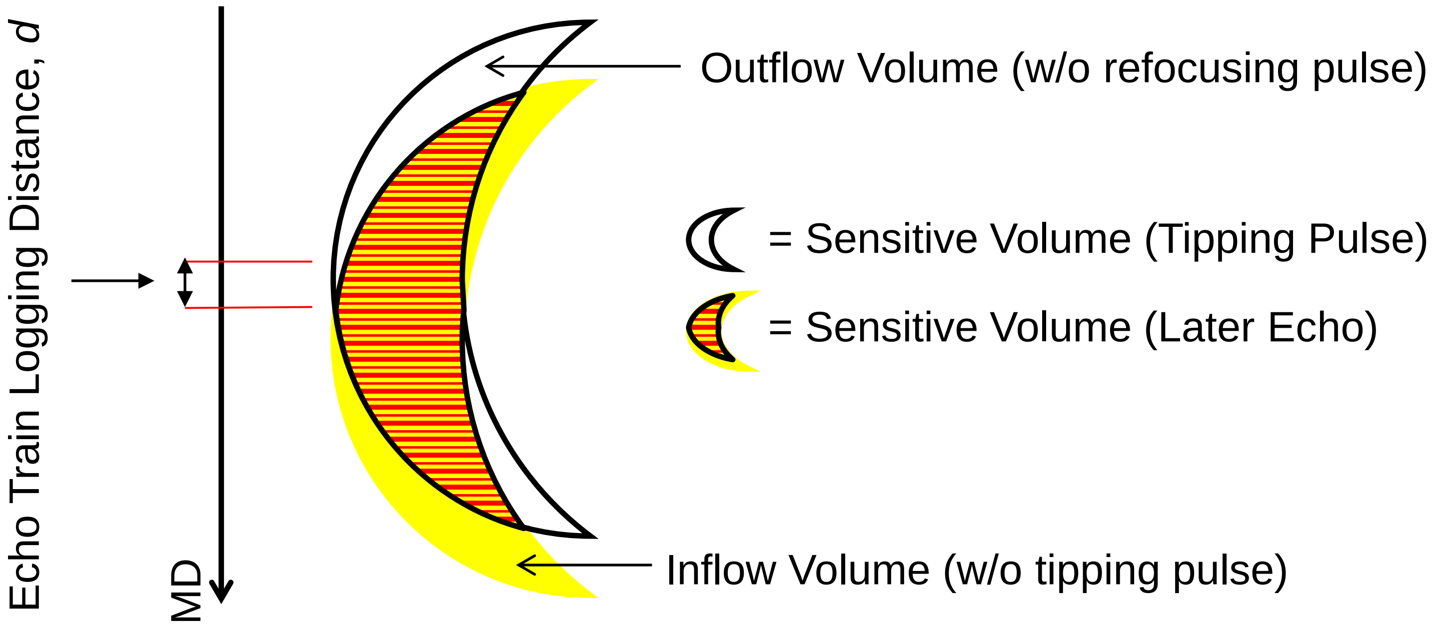


ROP - Interaction Volumes Without Motion



Coman et al., 2015, **SPE175050**

Flow Effect

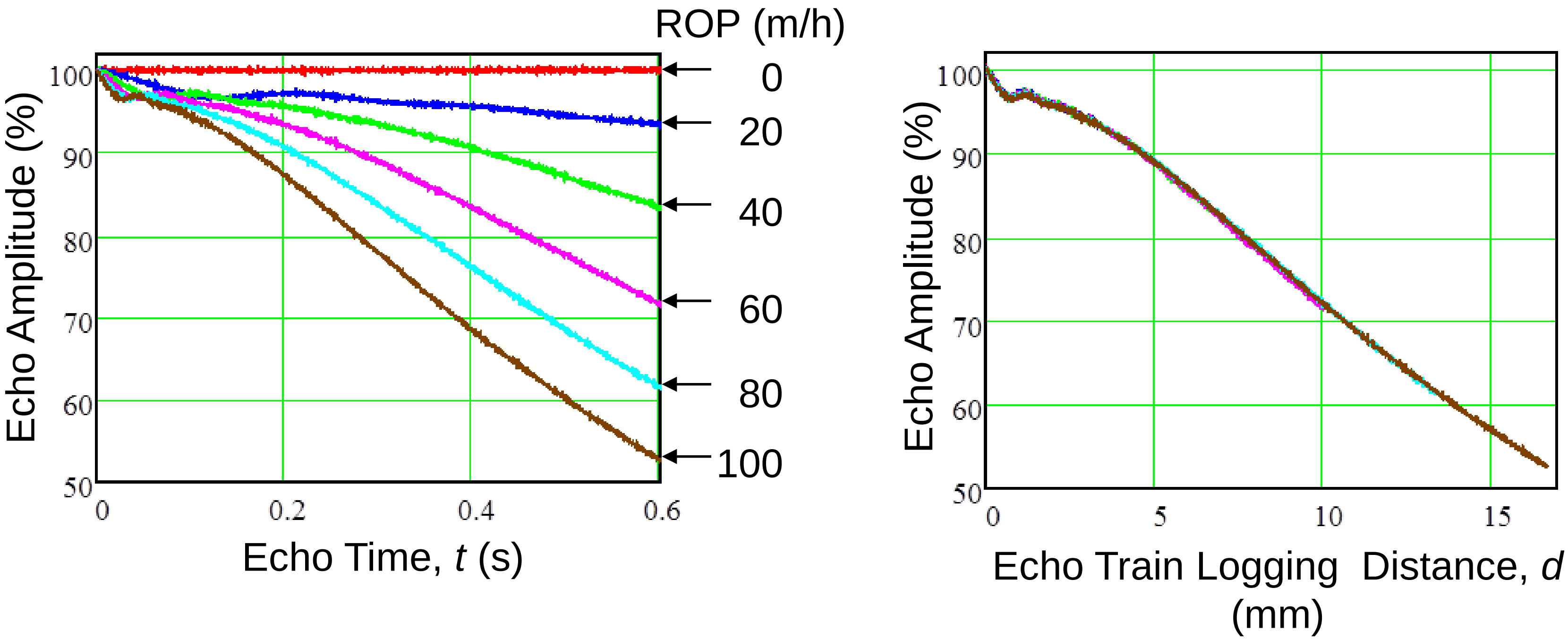


Coman et al., 2015, **SPE175050**

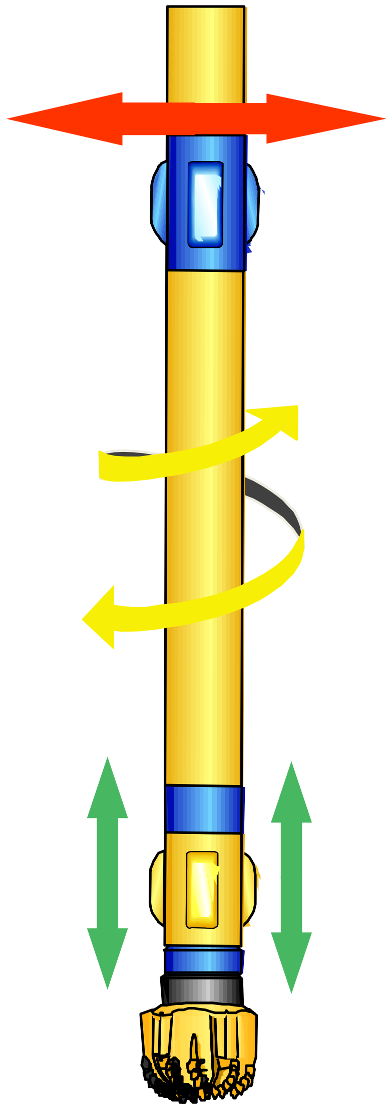
Flow Effect

- Outflow effect
  - w/o refocusing pulse
- Inflow effect
  - w/o tipping pulse
- Dephasing effect
  - cummulative effect of imperfect refocusing
  - relative motion hydrogen atom / NMR tool
  - similar to the NMR diffusion effect
  - $\sim ROP * (G * TE)^2$

Flow Effect

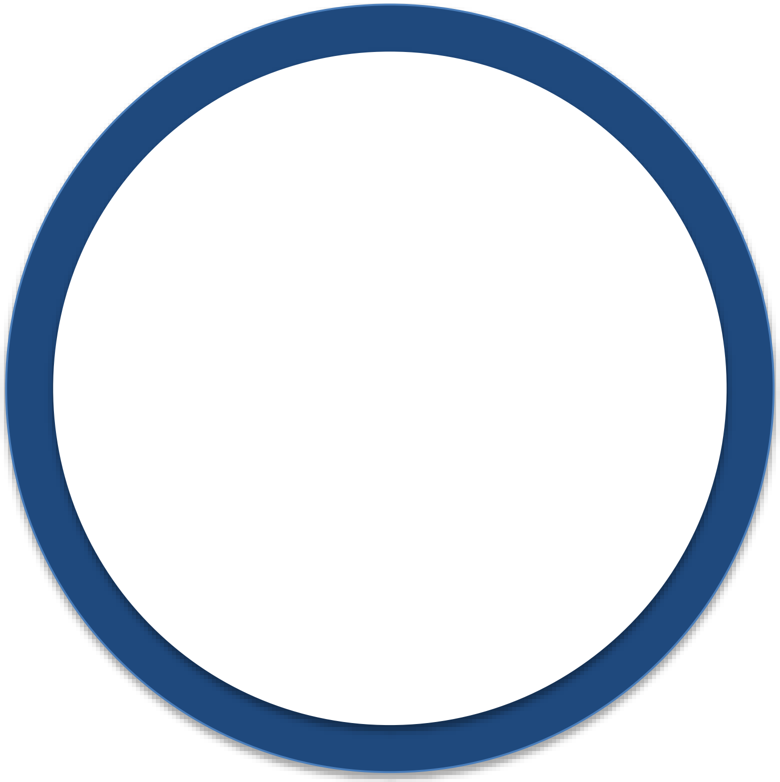


Coman et al., 2015, **SPE175050**

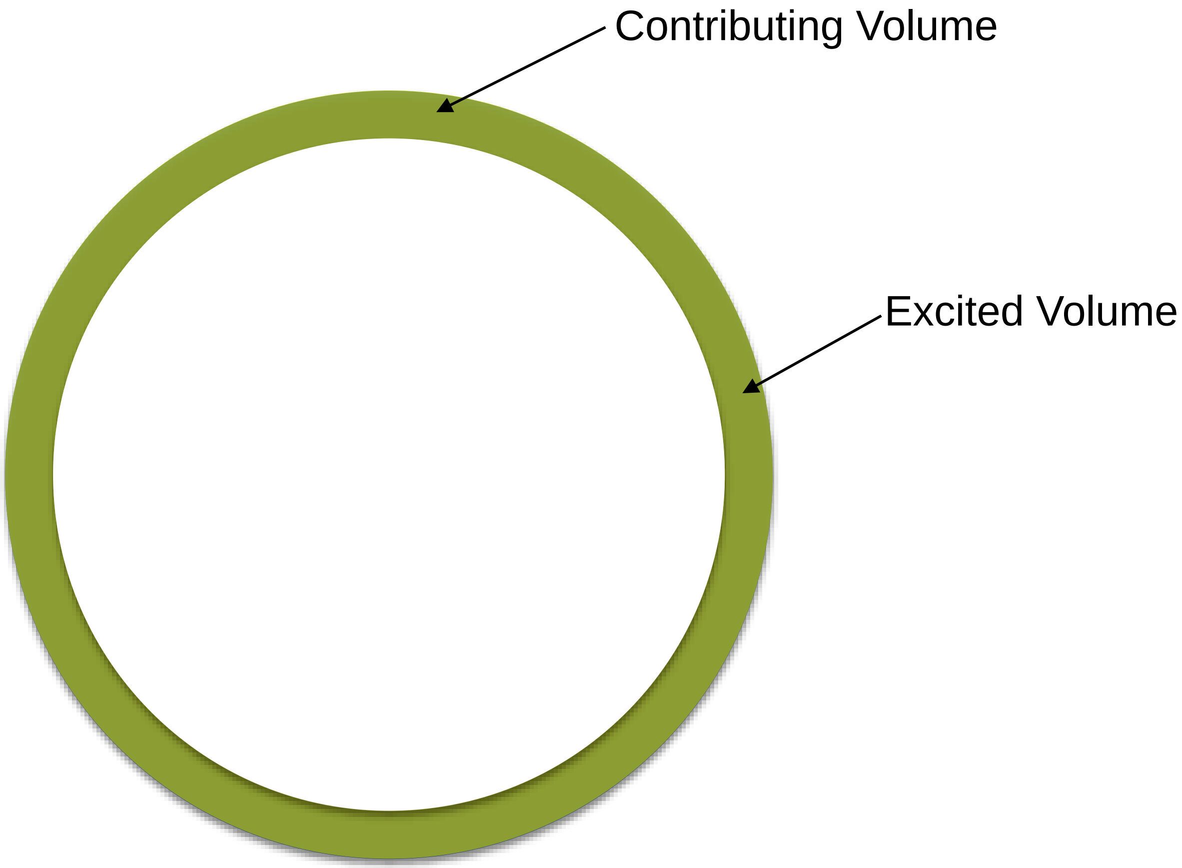

Lateral Vibration
Torsional Vibration
Axial Vibration

Lateral Motion

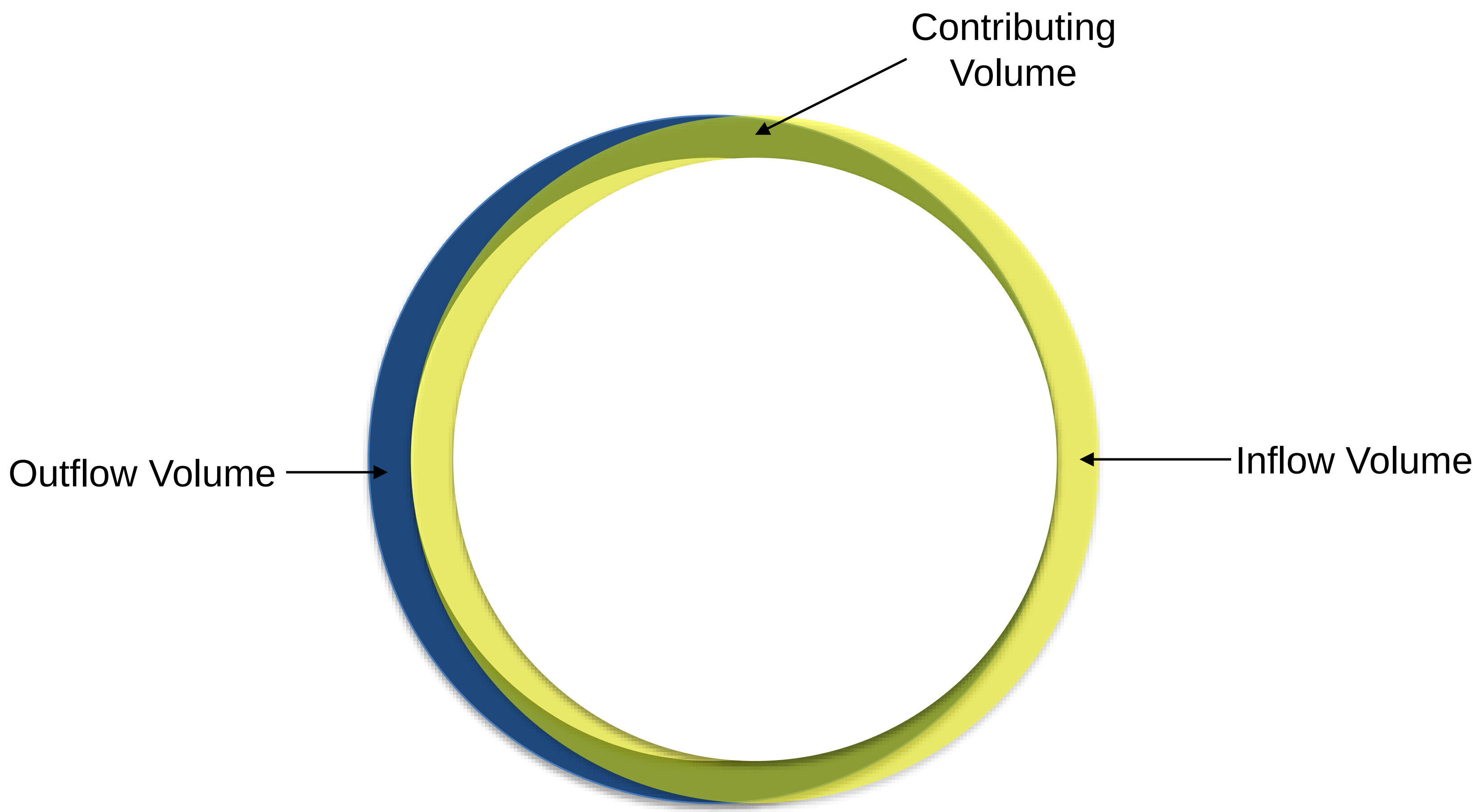
Top View on the Excited Region in NMR Antenna Plane



Top View on the Sensitive Region (Without Motion)

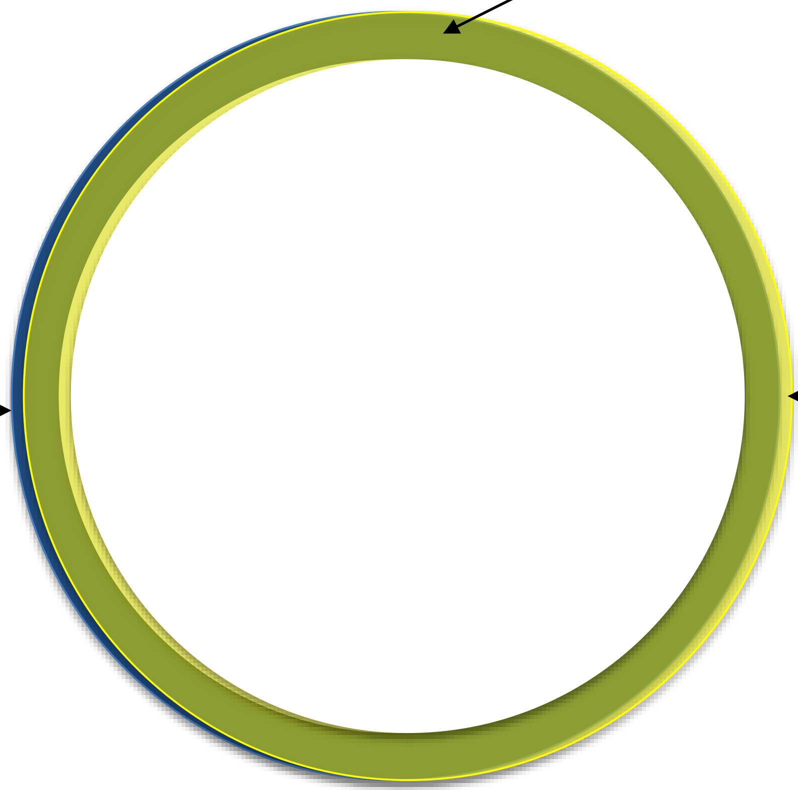


Lateral Motion 15mm



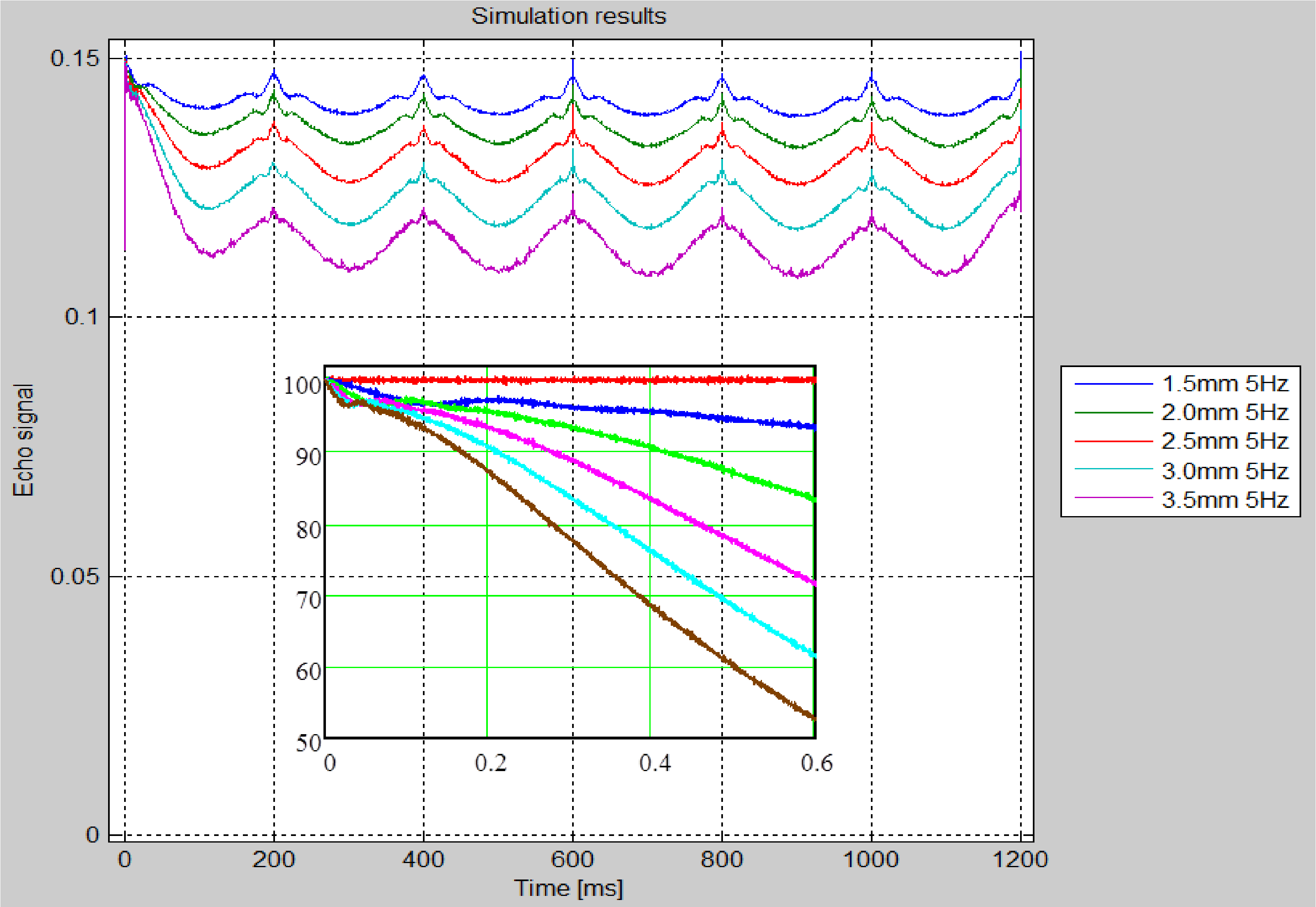
Amplitude of the echo is ~ contributing volume

Lateral Motion 3.5mm



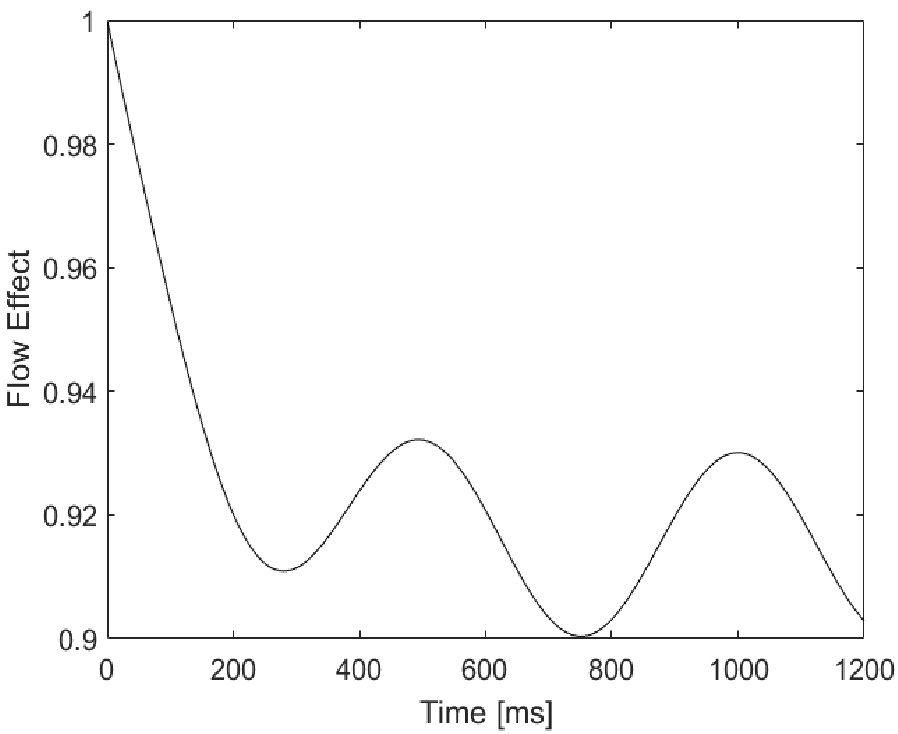
The “**dephasing effect**” is further reducing the echo amplitude

Simulation Results



Lateral-Motion Flow Effect

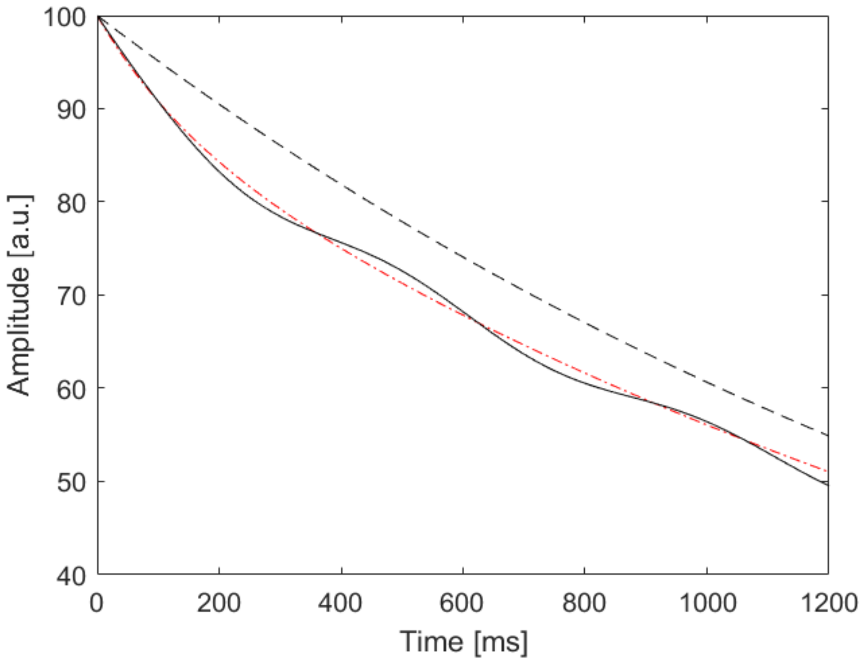
$$f(t) = 1 - A_{exp}\left(1 - e^{-\frac{t}{T_{exp}}}\right) - A_{cos}\left(1 - \cos\left(2\pi\frac{t}{T_{cos}}\right)\right)$$



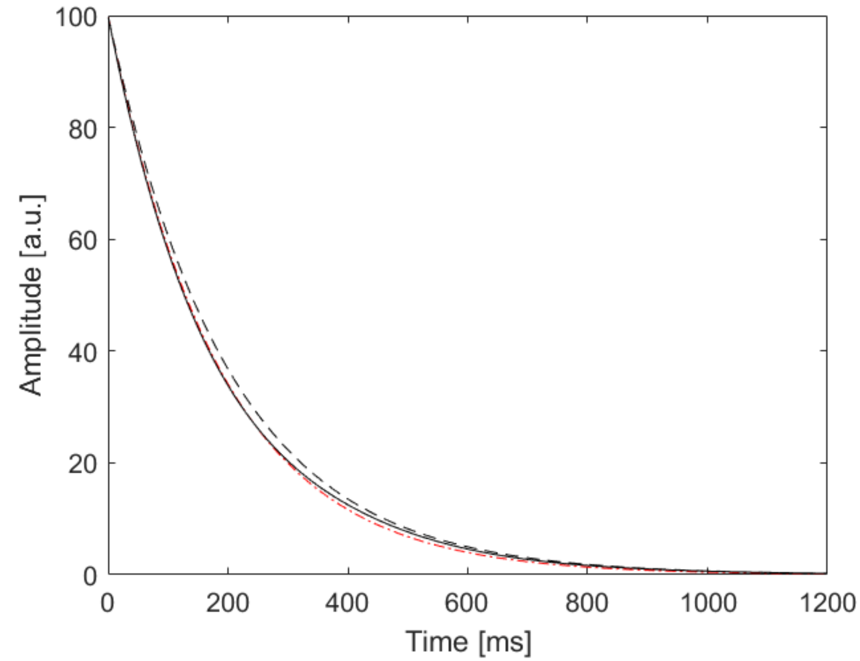
- $A_{exp} \sim$ lateral motion distance
- A_{cos} affects < 5% of porosity
- $T_{cos} \approx 1/\text{RPM}$
- $T_{exp} \approx 0.35 \cdot T_{cos}$

Lateral-Motion Flow Effect

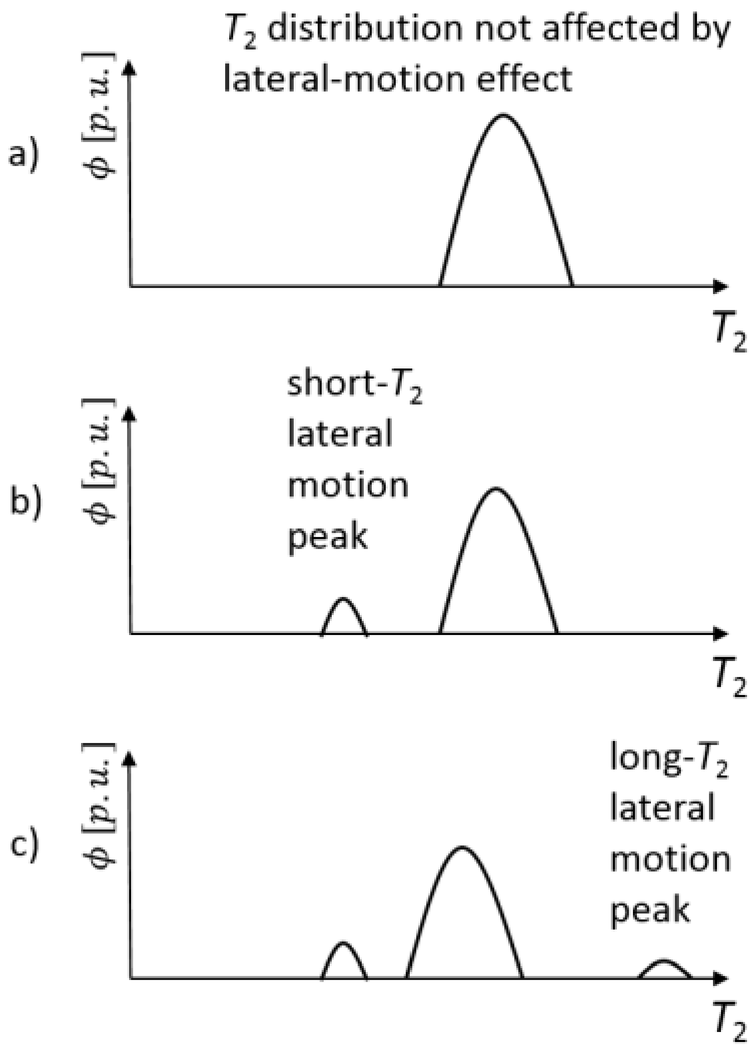
T_2 = 2 seconds



T_2 = 0.2 seconds



Effect of Lateral Motion on T2 Distribution (without correction)



NMR MOTION CORRECTION

Joint Inversion JI (Dunn et al., 1998)

$$b_i = \sum_{j=1}^{m} \phi_j e^{\frac{-iTE}{T_j}} \left(1 - e^{\frac{-TW}{r_j T_j}}\right)$$

$$\begin{bmatrix} k_{11} & k_{12} & \cdots & k_{1m} \\ \vdots & \vdots & \vdots \cdots & \cdots \\ \sigma l_{11} & \cdots & \cdots & \sigma l_{1m} \\ \vdots & \vdots & \vdots \cdots & \vdots \end{bmatrix} \begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} b_1 \\ \vdots \\ b_p \\ \sigma c_1 \\ \vdots \\ \sigma c_q \end{bmatrix}$$

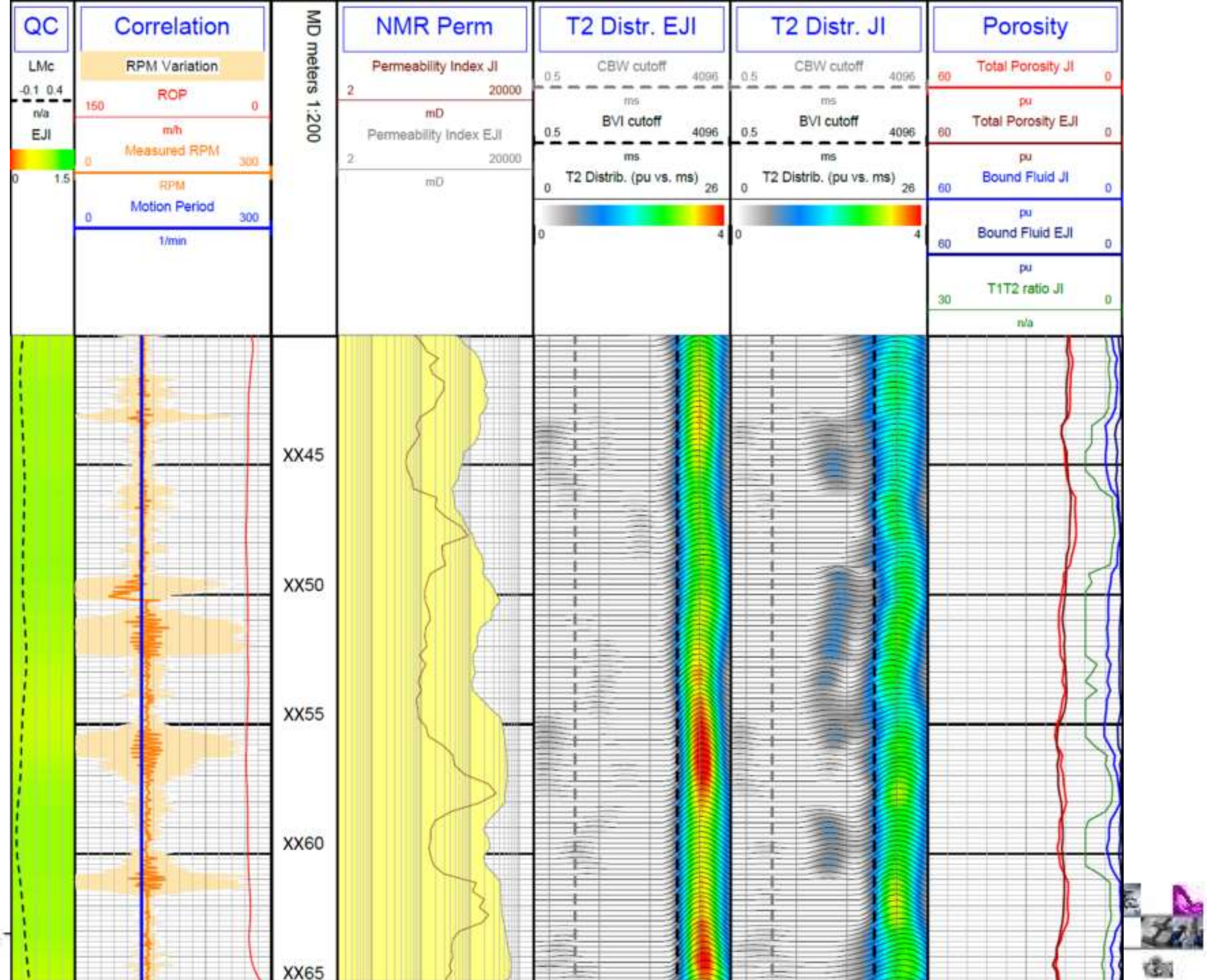
- Linear inversion
- $\{b_1, \ldots, b_i, \ldots, b_p\}$ echoes of the echo train
- $\{c_1, \ldots, c_i, \ldots, c_q\}$ echoes of the trainlet
- $\{y_1, \ldots, y_j, \ldots, y_m\}$ are *m* partial porosities
- σ is the ratio of the regular measurement error of the echo train and the regular measurement error of the trainlet
- $k_{ij} = \left(1 - e^{-TW_{ET}/rT_j}\right) e^{-iTE_{ET}/T_j}$
- $l_{ij} = \left(1 - e^{-TW_{Tr}/rT_j}\right) e^{-iTE_{Tr}/T_j}$

Expanded Joint Inversion (EJI)

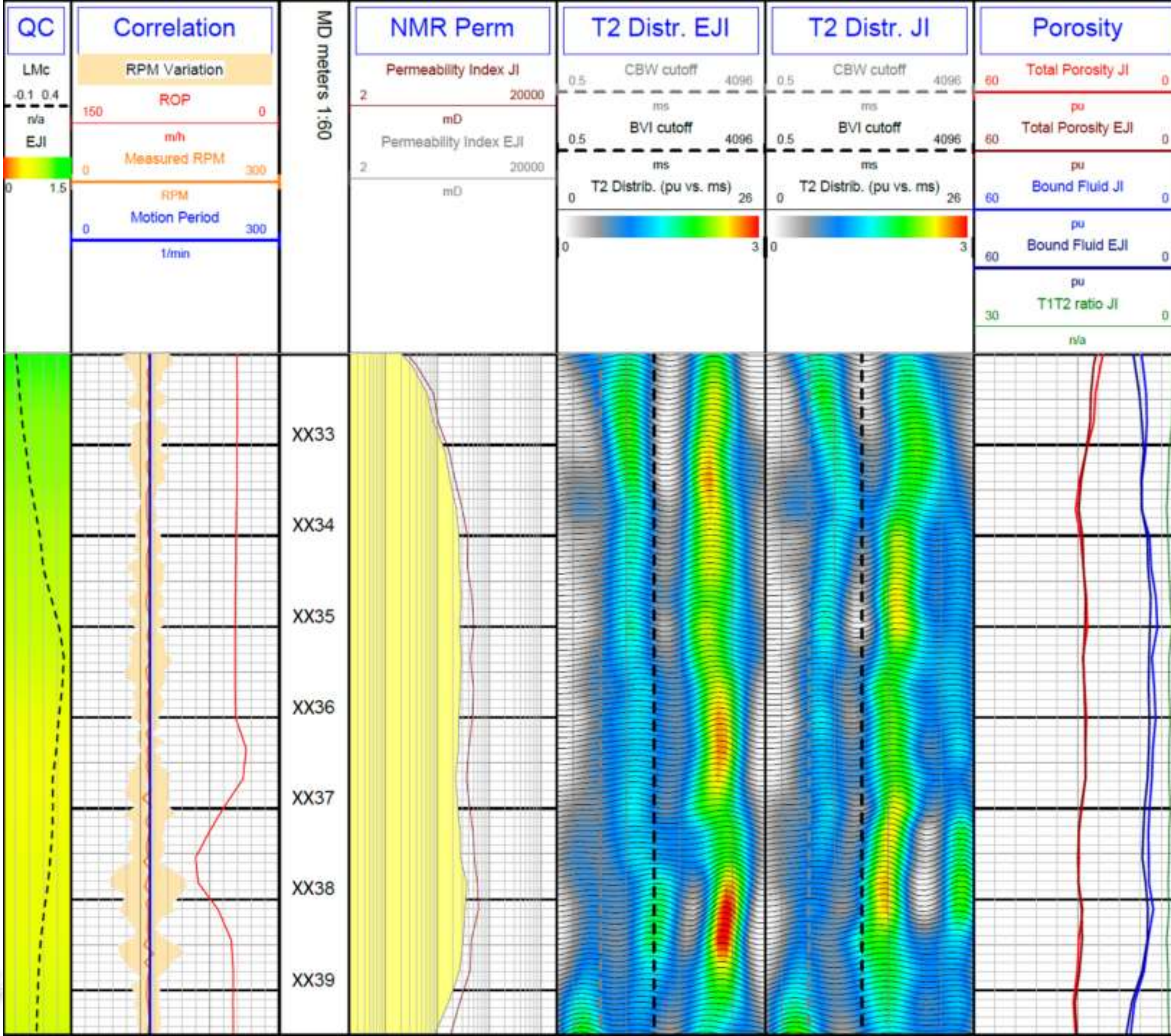
$$b_i = f\left(iTE, A_{exp}, T_{exp}, A_{cos}, T_{cos}\right) \sum_{j=1}^{m} \phi_j e^{\frac{-iTE}{T_j}} \left(1 - e^{\frac{-TW}{r_j T_j}}\right)$$

- *Non-linear inversion*
- *The* ***global inversion***
  - $A_{exp}, T_{exp}, A_{cos}, T_{cos}, r_{BVI}, r_{BVM}$
  - Non-linear system → Levenberg–Marquardt optimization algorithm
- *The* ***level-by-level inversion***
  - Provides the partial porosities, ϕ_i, of the T_2 distribution

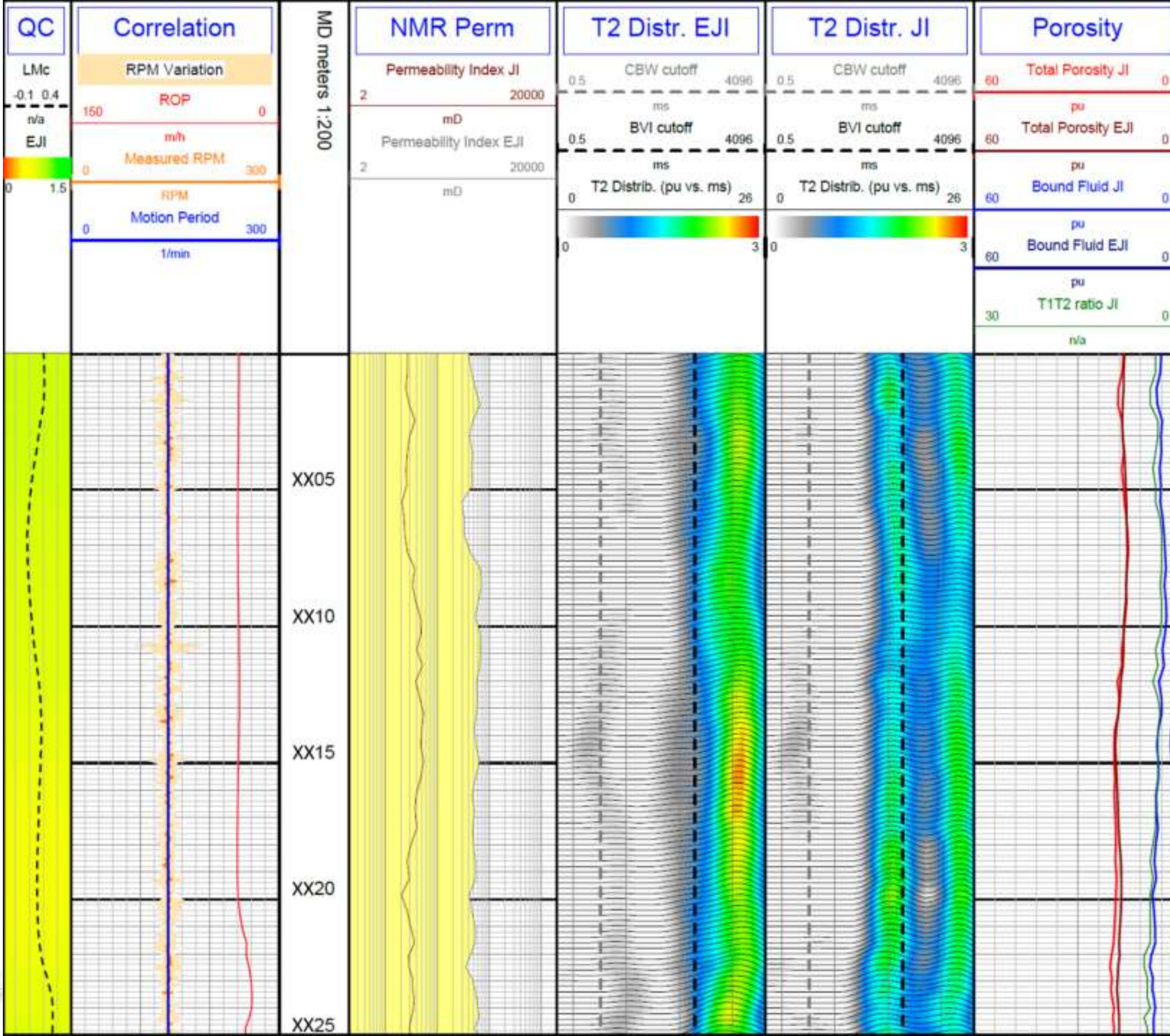
DATA EXAMPLES


QC
Correlation
NMR Perm
T2 Distr. EJI
T2 Distr. JI
Porosity
LMc
-0.1 0.4
n/a
EJI
0 1.5
RPM Variation
ROP
150 0
m/h
Measured RPM
0 300
RPM
Motion Period
0 300
1/min
MD meters 1:200
Permeability Index JI
2 20000
mD
Permeability Index EJI
2 20000
mD
CBW cutoff
0.5 4096
ms
BVI cutoff
0.5 4096
ms
T2 Distrib. (pu vs. ms)
0 26
0 4
Total Porosity JI
60 0
pu
Total Porosity EJI
60 0
pu
Bound Fluid JI
60 0
pu
Bound Fluid EJI
60 0
pu
T1T2 ratio JI
30 0
n/a
XX45
XX50
XX55
XX60
XX65

NFES


QC
LMc
-0.1 0.4
n/a
EJI
0 1.5
Correlation
RPM Variation
ROP
150 0
m/h
Measured RPM
0 300
RPM
Motion Period
0 300
1/min
MD meters 1:60
XX33
XX34
XX35
XX36
XX37
XX38
XX39
NMR Perm
Permeability Index JI
2 20000
mD
Permeability Index EJI
2 20000
mD
T2 Distr. EJI
CBW cutoff
0.5 4096
ms
BVI cutoff
0.5 4096
ms
T2 Distrib. (pu vs. ms)
0 26
0 3
T2 Distr. JI
CBW cutoff
0.5 4096
ms
BVI cutoff
0.5 4096
ms
T2 Distrib. (pu vs. ms)
0 26
0 3
Porosity
Total Porosity JI
60 0
pu
Total Porosity EJI
60 0
pu
Bound Fluid JI
60 0
pu
Bound Fluid EJI
60 0
pu
T1T2 ratio JI
30 0
n/a

NFES


QC
LMc
-0.1 0.4
n/a
EJI
0 1.5
Correlation
RPM Variation
ROP
150 0
m/h
Measured RPM
0 300
RPM
Motion Period
0 300
1/min
MD meters 1:200
XX05
XX10
XX15
XX20
XX25
NMR Perm
Permeability Index JI
2 20000
mD
Permeability Index EJI
2 20000
mD
T2 Distr. EJI
CBW cutoff
0.5 4096
ms
BVI cutoff
0.5 4096
ms
T2 Distrib. (pu vs. ms)
0 26
0 3
T2 Distr. JI
CBW cutoff
0.5 4096
ms
BVI cutoff
0.5 4096
ms
T2 Distrib. (pu vs. ms)
0 26
0 3
Porosity
Total Porosity JI
60 0
pu
Total Porosity EJI
60 0
pu
Bound Fluid JI
60 0
pu
Bound Fluid EJI
60 0
pu
T1T2 ratio JI
30 0
n/a

NFES

Summary

- Lateral motion of NMR tool → **lateral-motion flow effect**
- Lateral-motion flow effect:
  - Barely change the NMR total porosity
  - Might change the T_2 distribution
  - Can be described by a **four-parametric function**
- Motion parameters are **extracted from NMR data**
- Extraction by **expanded joint inversion (EJI)**
- EJI improves the T_2 distribution
  - Bound & movable fluids
  - Permeability
  - Saturation
  - Oil viscosity