

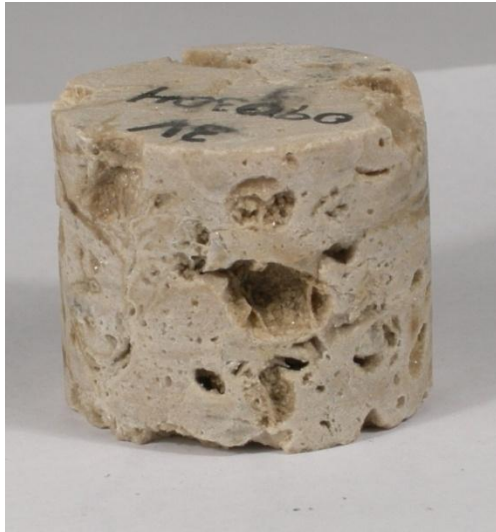
Pore structure of vuggy carbonates and rate dependent displacement in carbonate rocks

**Neeraj Rohilla
Dr. George J. Hirasaki
Rice University, 04/26/2011**

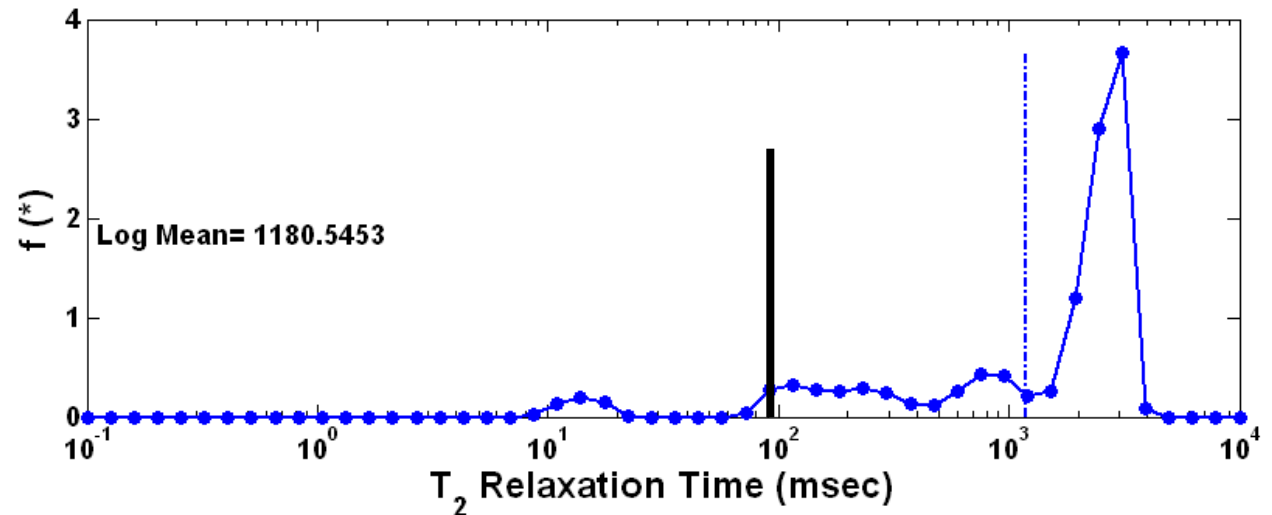
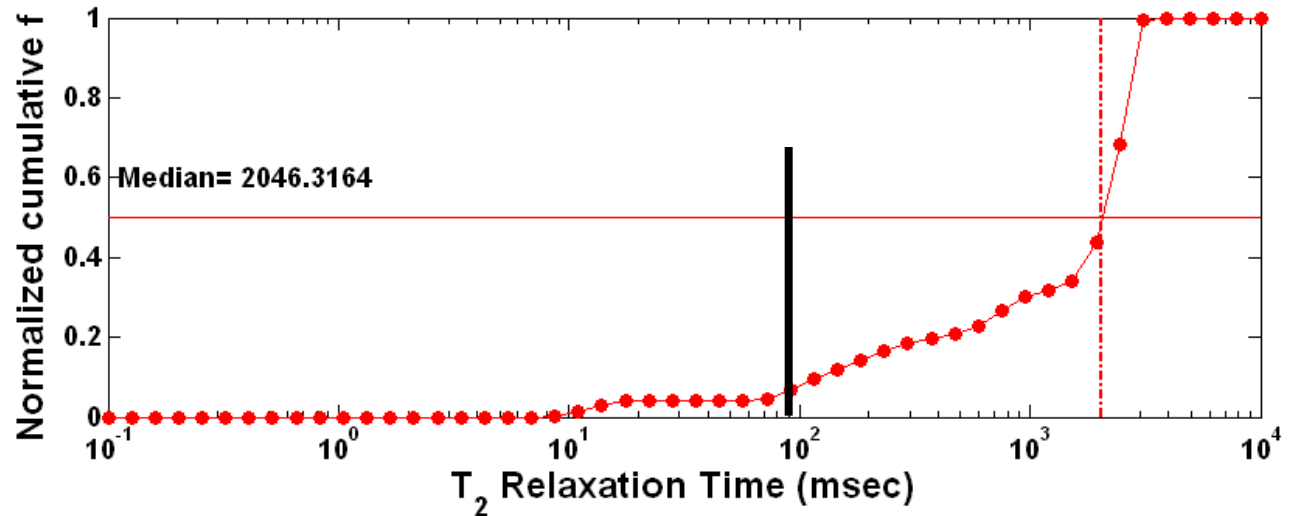
Outline

- **NMR Results**
- **Tracer Experiments**
 - **Theory**
 - **Procedure**
- **1D Sandpack**
- **1D Heterogeneous Sandpack**
- **Experiments on 1.5 inch diameter samples**
- **Experiments on 3.5 inch diameter samples**
- **Recovery Efficiency**
- **Flow rate and Mass Transfer**
- **Conclusions**

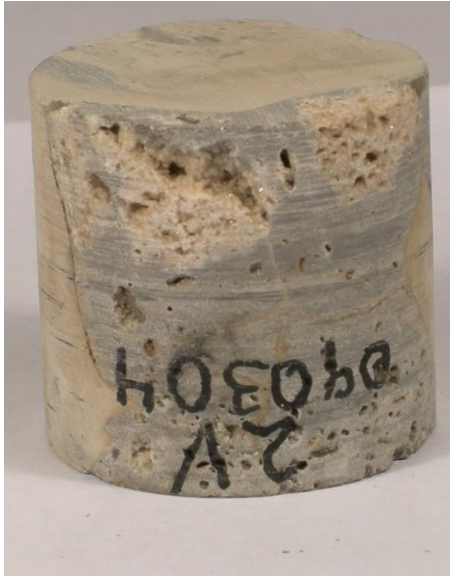
T_2 Relaxation time spectrum for core-plug saturated with 1% brine



Core-Plug ID: 3V
Permeability: 6 mD

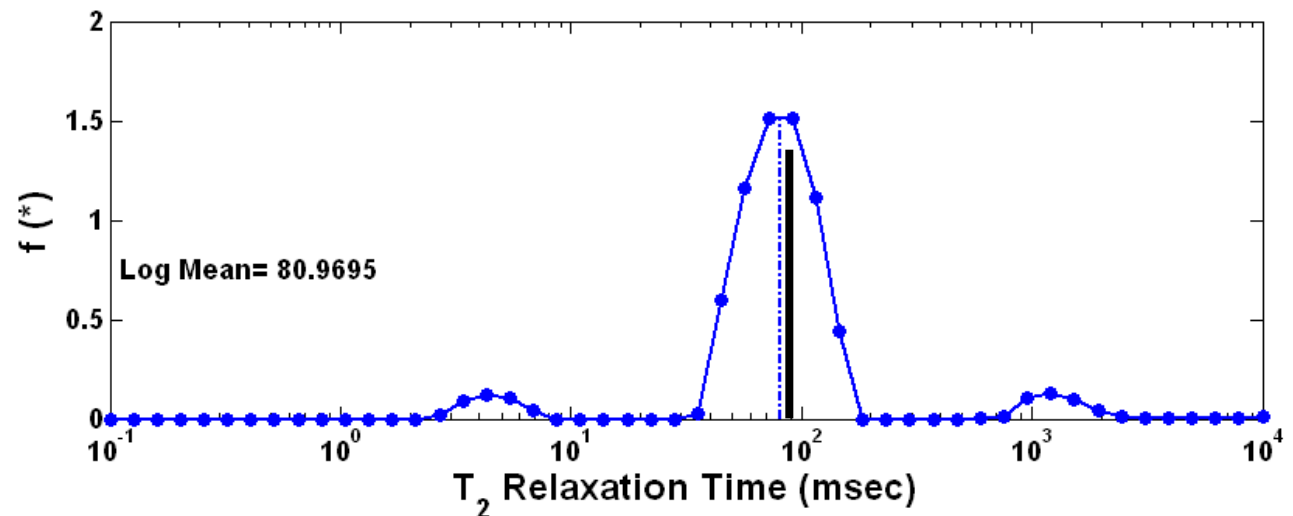
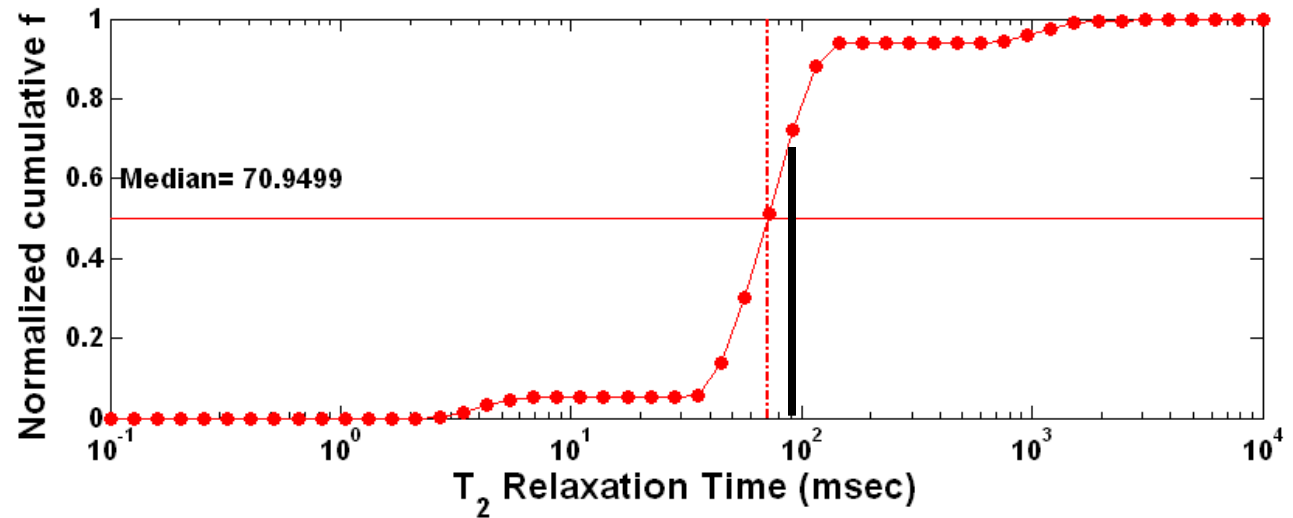


T_2 Relaxation time spectrum for core-plug saturated with 1% brine

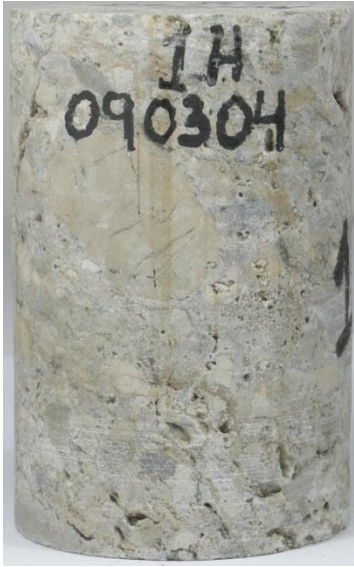


Core-Plug ID: 2V

Permeability: 2 mD

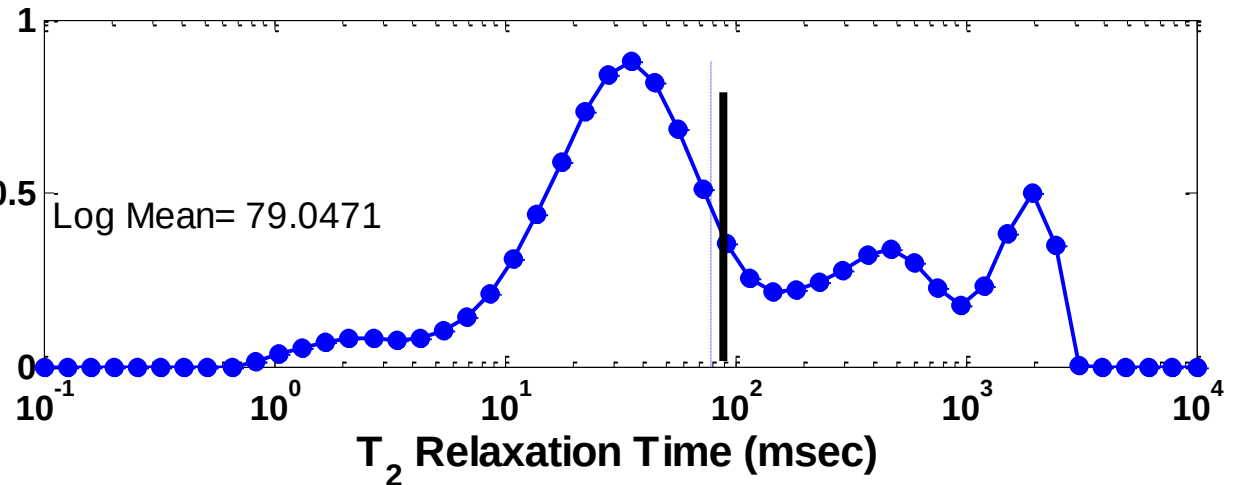
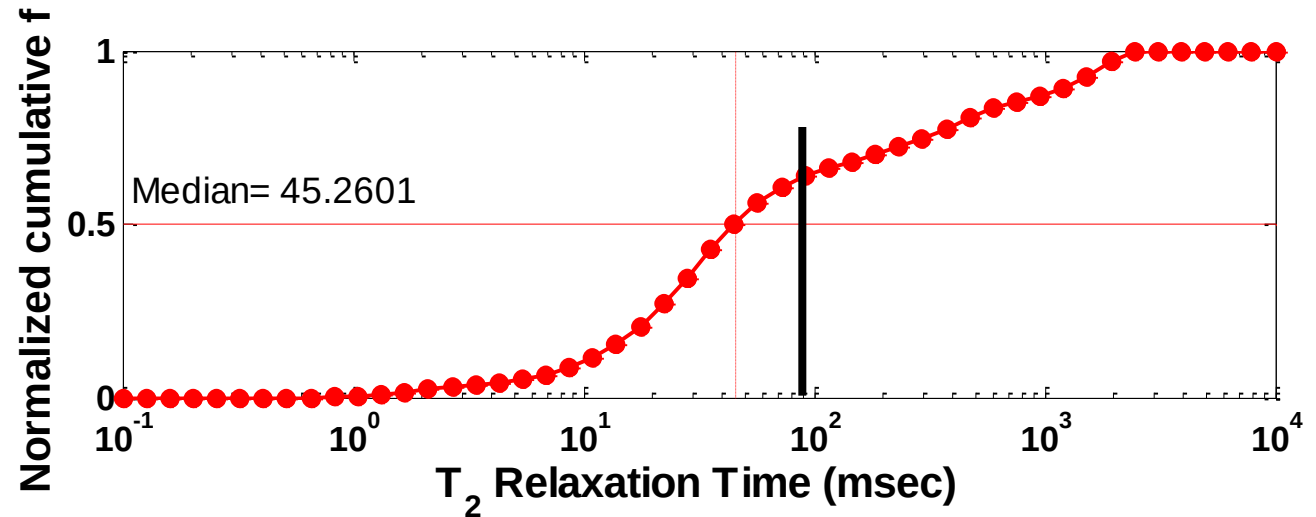


T_2 Relaxation time spectrum for core-plug saturated with 1% brine

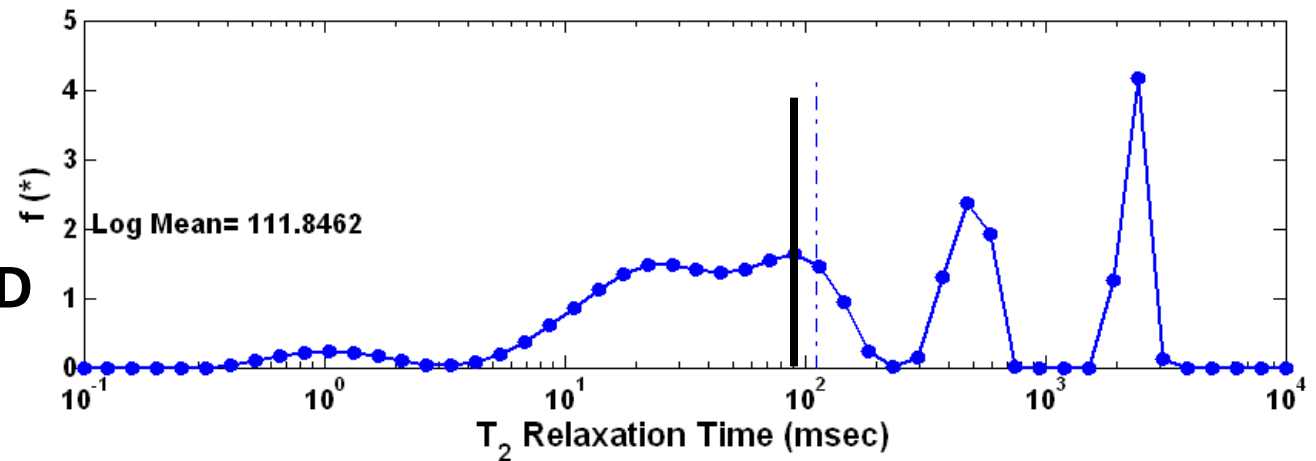
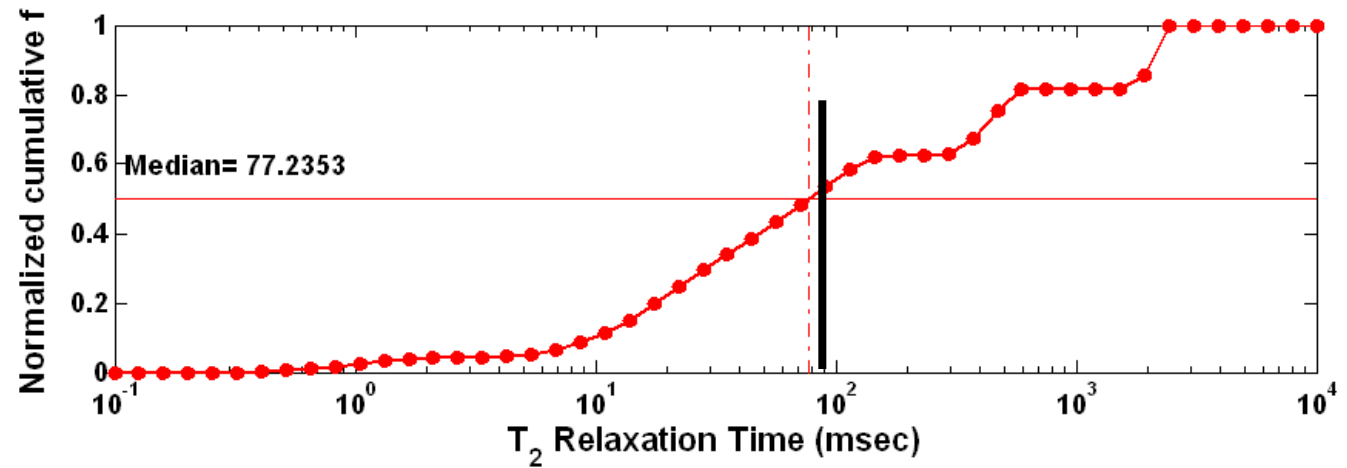


Core-Plug ID: 1H

Permeability: 2.1 mD



T_2 Relaxation time spectrum for core-plug saturated with 1% brine



Core-Plug ID: 1HA

Permeability: 1.7 mD

T₂ Relaxation time spectrum for core-plug saturated with 1% brine

S. No.	Core ID	T2 Log Mean (ms)	Permeability (mD)
1	3V	1180	6
2	2V	81	2
3	2VA	637	4
4	1H	79	4
5	1HA	112	1.7
6	6H	436	45
7	6HA	-	510

Tracer Analysis

- 1) The differential capacitance model developed by Coats & Smith (1964) is used to characterize dispersion and dead end pore volume.
- 2) The Coats and Smith model is introduced by two equations:

$$f \frac{\partial c}{\partial t} + (1-f) \frac{\partial c^*}{\partial t} = K \frac{\partial^2 c}{\partial x^2} - \frac{u}{\phi} \frac{\partial c}{\partial x}$$

$$(1-f) \frac{\partial c^*}{\partial t} = M(c - c^*)$$

Where, K = Dispersion coefficient

$(1-f)$ = Fraction of dead end pores

M = Mass transfer coefficient

c = tracer concentration in flowing stream

c^* = tracer concentration in stagnant volume

u = superficial velocity

ϕ = porosity

$v = \frac{u}{\phi}$ = interstitial velocity

➤ **Boundary and Initial conditions**

$$c(0, t) = c_{BC}$$

$$c(\infty, t) = c_{IC}$$

$$c(x, 0) = c_{IC}$$

$$c^*(x, 0) = c_{IC}$$

• c_{IC} is initial concentration in system

• c_{BC} is injected concentration at the inlet

➤ **Dimensionless variables and groups:**

$$\hat{x} = \frac{x}{L}, \hat{t} = \frac{t}{t_0} \text{ where, } t_0 = \frac{L}{v} \quad \hat{t} = \text{Pore volume throughput}$$

$$\hat{c} = \left(\frac{c - c_{IC}}{c_{BC} - c_{IC}} \right) \text{ and } \hat{c}^* = \left(\frac{c^* - c_{IC}}{c_{BC} - c_{IC}} \right)$$

$$f, N_M = \frac{ML}{v} \text{ and } N_K = \frac{K}{Lv} = \frac{\alpha}{L}$$

Tracer Analysis

- Differential equations are solved using Laplace Transform:

$$\mathcal{L}(\hat{c}) = \left(\frac{1}{\hat{s}} \right) \exp \left[\left(\frac{\hat{x}}{2N_K} \right) \left(1 - \sqrt{1 + 4N_K \hat{s} \left(f + \frac{N_M}{\hat{s} + \frac{N_M}{1-f}} \right)} \right) \right]$$

- Experimental data is numerically transformed into Laplace domain
- Model parameters are obtained by fitting the experimental data in Laplace domain using Lavenberg-Marquardt algorithm

Improved algorithm for unique parameter estimation

- Using experimental data at two different flow rates.
- Mass transfer coefficient (M) is independent of interstitial velocity and dispersion coefficient (K) varies linearly with interstitial velocity

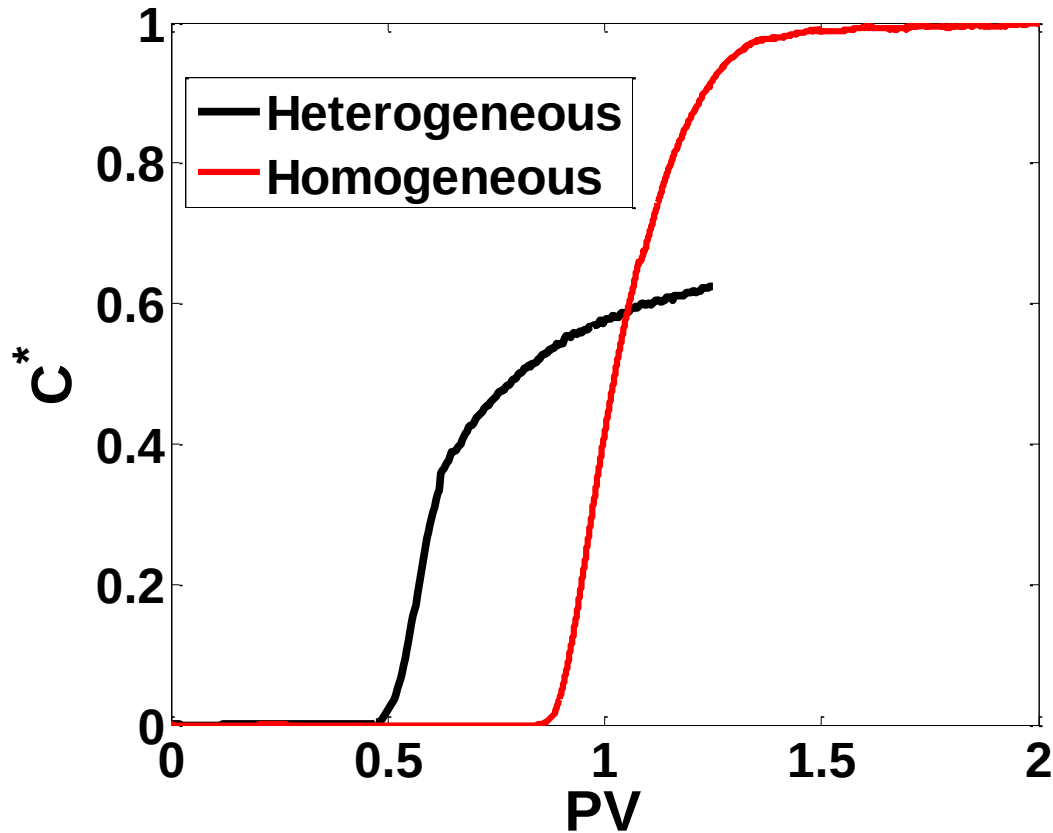
$$K \propto v \text{ and } M \neq M(v)$$

$$N_M = \frac{ML}{v} \text{ and } N_K = \frac{K}{Lv} = \frac{\alpha}{L}$$

$$N_M \propto \frac{1}{v} \text{ and } N_K \text{ is independent of } v$$

- Parameters are obtained for two sets of experiments simultaneously.

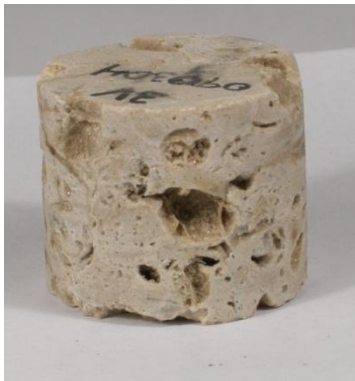
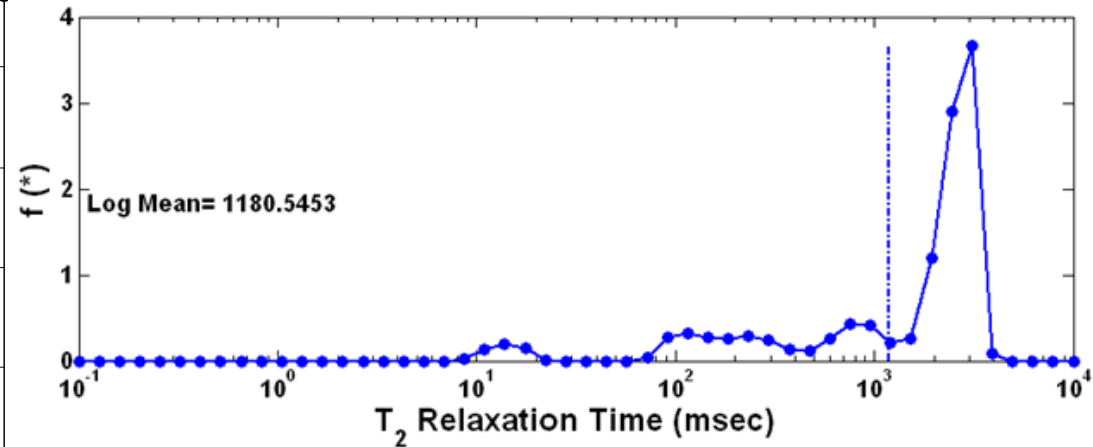
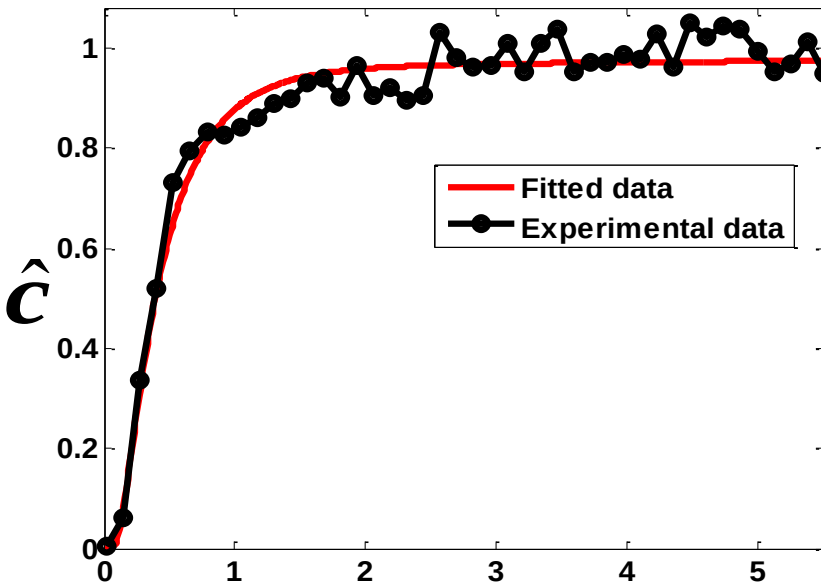
Tracer flow experiments on 1D sandpacks



- Heterogeneous sandpack
- Two sand layers of permeability contrast of 19
- Early breakthrough and a delayed response
- $f = 0.998$ (Homogeneous)
- $f = 0.65$ (Heterogeneous)



Tracer flow experiments on 1.5 inch diameter cores



$\hat{t}$ (PV)

$f = 0.5$ Flowing Fraction (f) : 0.5

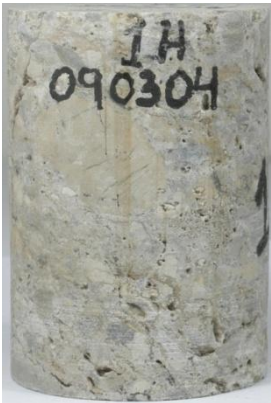
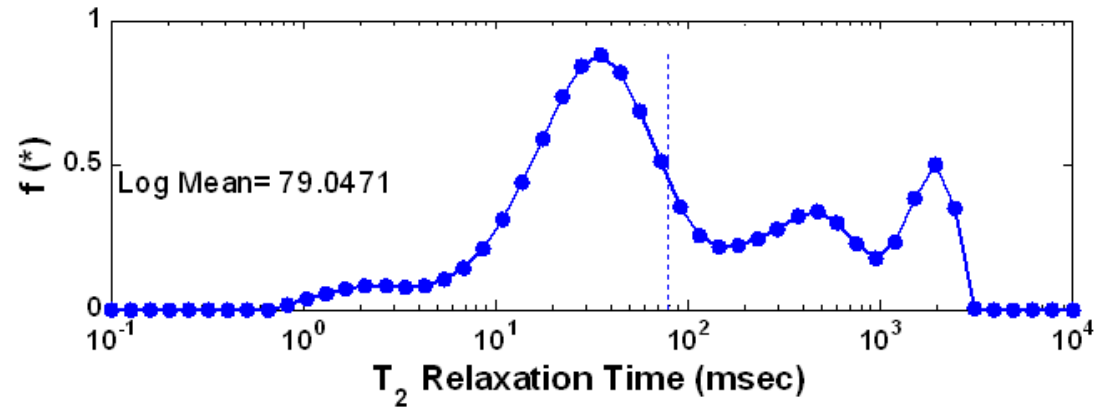
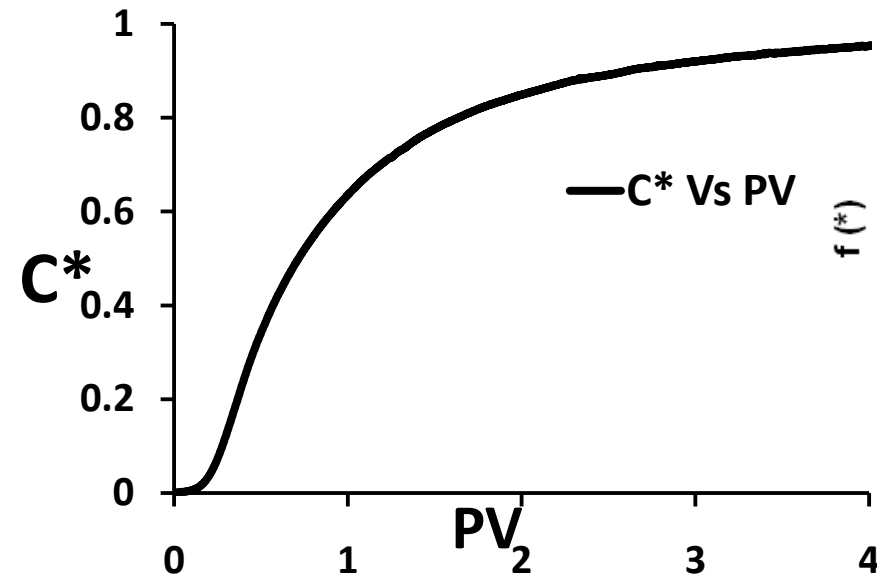
$N_K = 0.31$ Dispersivity (α) = 1 cm

$N_M = 0.04$ Mass transfer coefficient (M) = $6.6E-5 \text{ sec}^{-1}$

Core ID: 3V

Permeability: 6 mD

Tracer flow experiments on 1.5 inch diameter cores



$$f = 0.205$$

$$N_K = 0.01$$

$$N_M = 2.28$$

Flowing Fraction (f) : 0.205

Dispersivity (α) = 0.06 cm

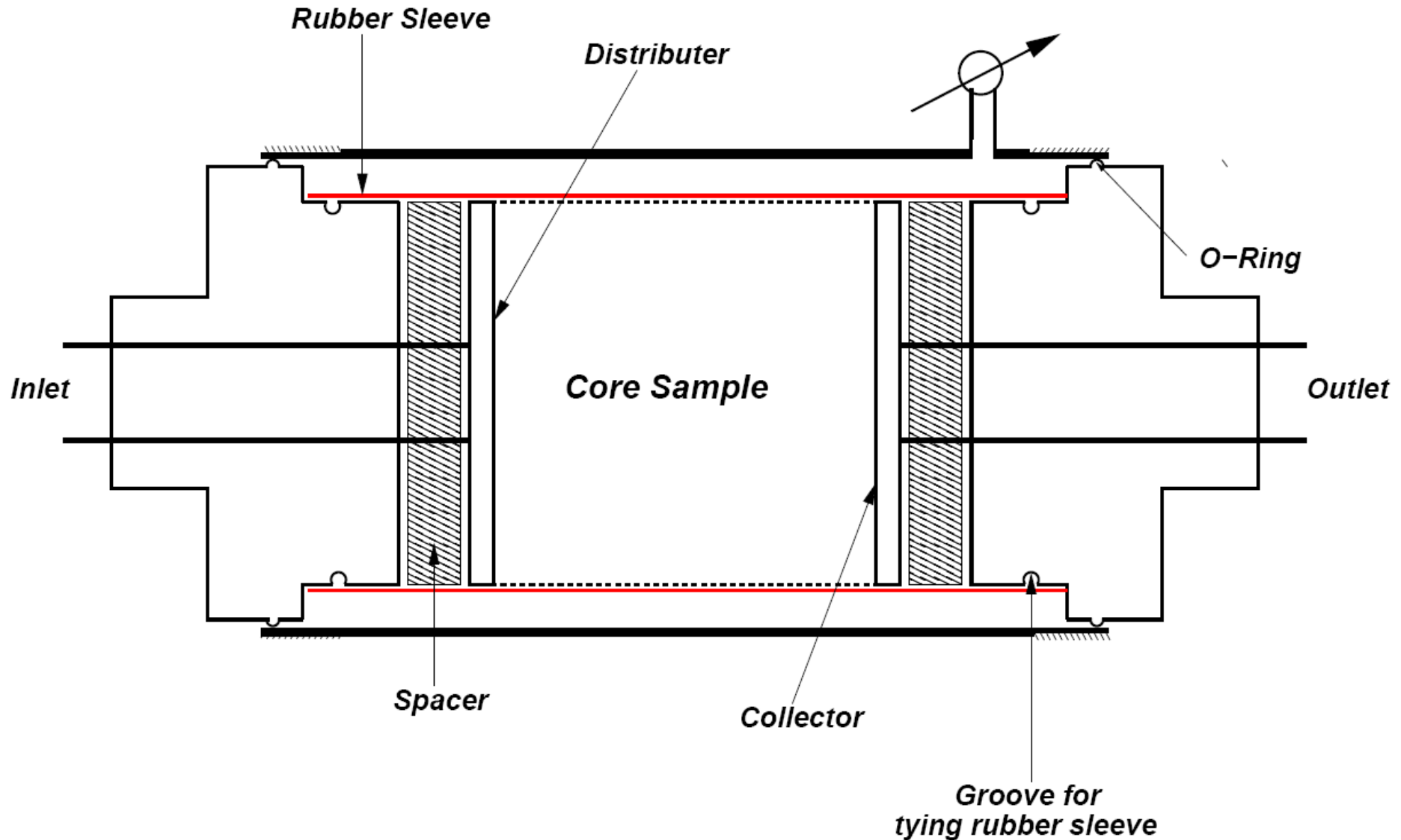
Mass transfer coefficient (M) = $7.1873E-4 \text{ sec}^{-1}$

Core ID: 1H

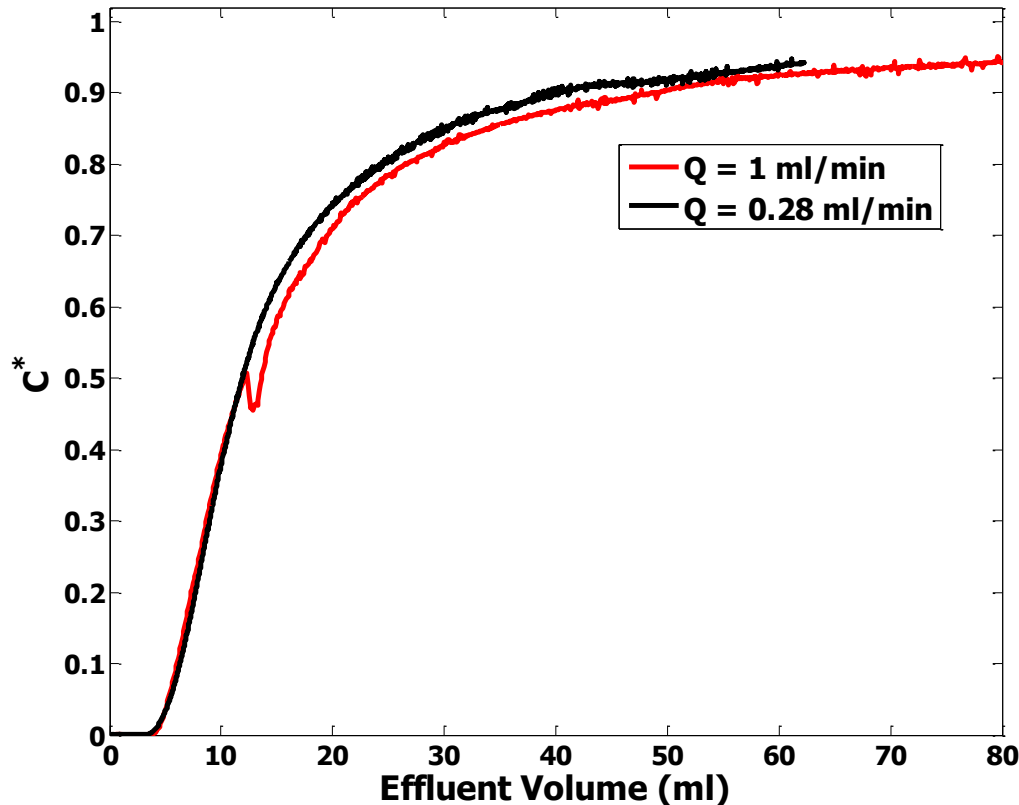
Permeability: 2.1 mD

T_2 Log-mean = 80 ms

Setup for flow experiments for larger diameter cores (3.5 and 4.0 inch)



Tracer flow experiment at two different flow rates (Sample: 3.5_A)



Sample : 3.5_A

Diameter : 3.5 inch

Length = 3.75 inch

Porosity = 7 %

Permeability = 213 mD

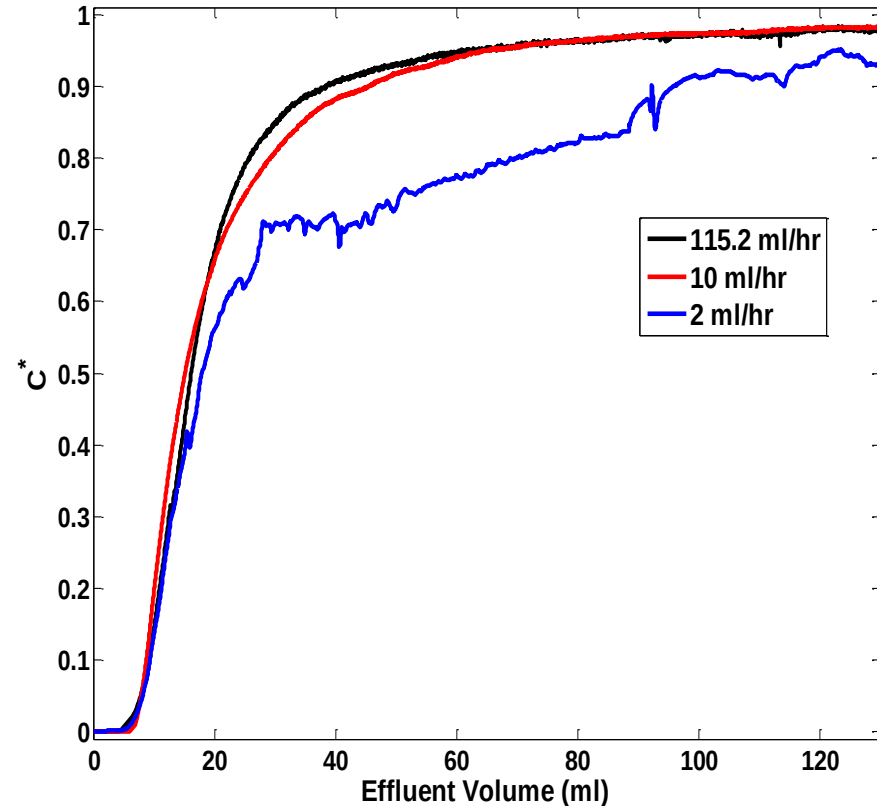
Pore Volume = 41 ml

$f = 0.41$ Flowing Fraction (f) : 0.412

$N_K = 0.316$ Dispersivity (α) = 3 cm

$N_M = 0.01$ Mass transfer coefficient (M) = $4.03\text{E-}6 \text{ sec}^{-1}$, $1/M \text{ (day)} = 2.86$

Comparison of tracer floods at different flowrates (Sample: 3.5_B)



Sample : 3.5_B

Diameter : 3.5 inch

Length = 3.75 inch

Porosity = 7 %

Permeability = 317 mD

Pore Volume = 41 ml

○ **2 ml/hr ~ 0.36 ft/day**

○ **10 ml/hr ~ 1.8 ft/day**

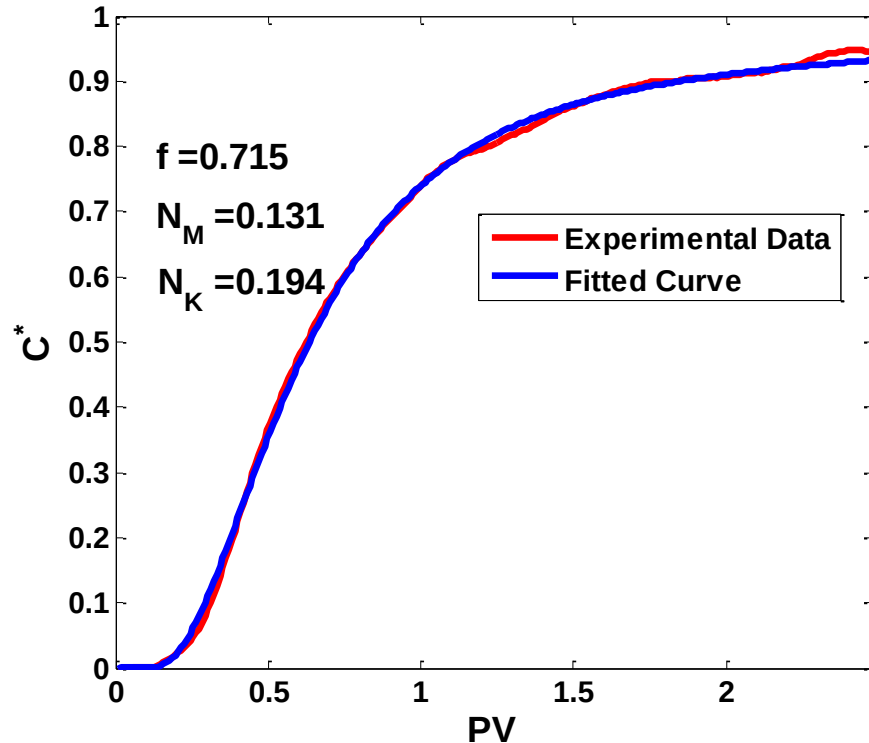
○ **115.2 ml/hr ~ 21 ft/day**

$f = 0.47$ Flowing Fraction (f) : 0.48

$N_K = 0.183$ Dispersivity (α) = 1.7 cm

**$N_M = 0.0059$ Mass transfer coefficient (M) = $4.6E-6 \text{ sec}^{-1}$,
 $1/M \text{ (day)} = 1.6$**

Tracer flow experiment at slow rate (Sample: 3.5_C)



Sample : 3.5_C

Diameter : 3.5 inch

Length = 3.75 inch

Porosity = 6.7 %

Pore Volume = 39.8 ml

$f = 0.71$ Flowing Fraction (f) : 0.71

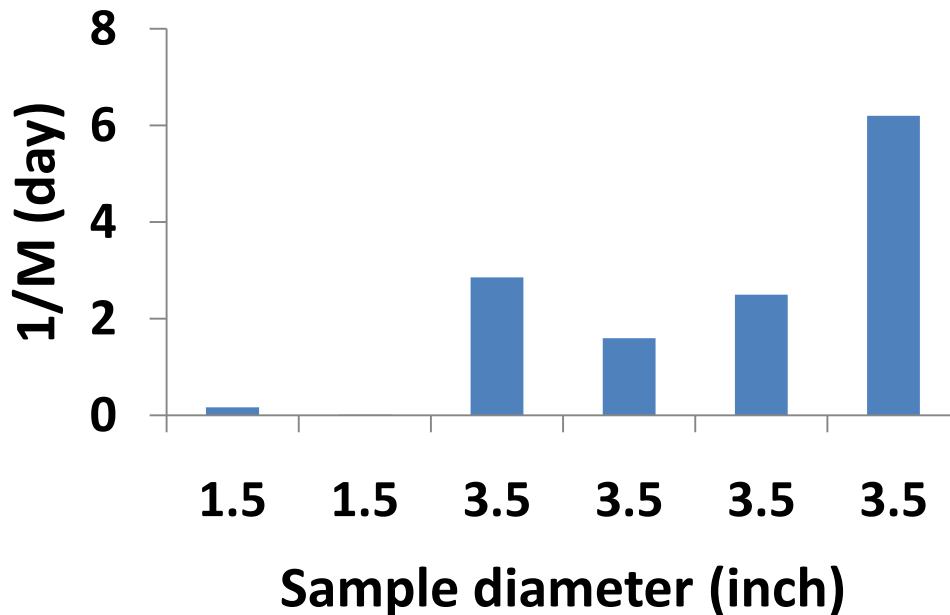
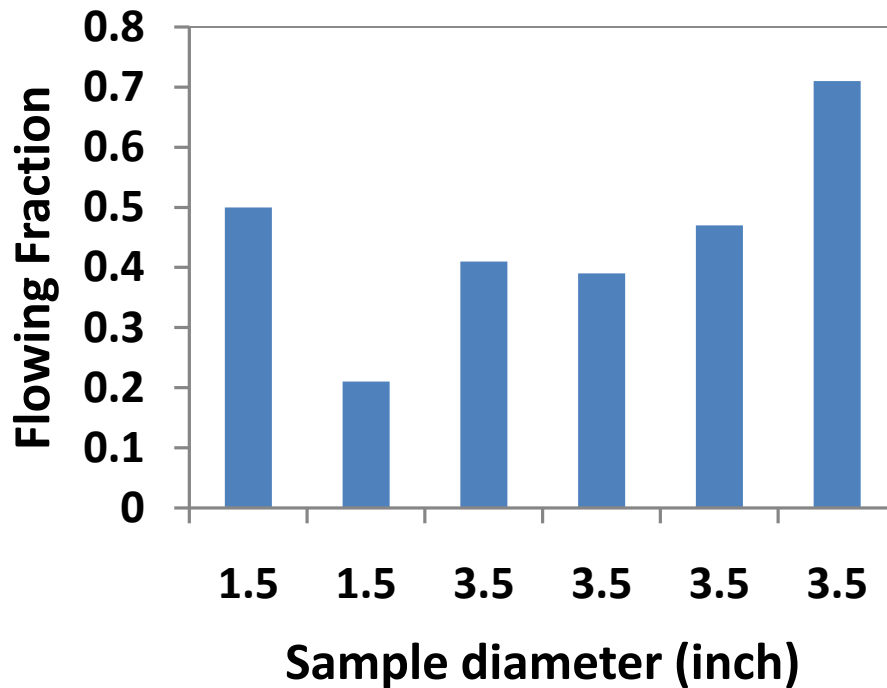
$N_K = 0.19$ Dispersivity (α) = 1.8 cm

**$N_M = 0.13$ Mass transfer coefficient (M) = $1.9E-6 \text{ sec}^{-1}$,
1/ M (day) = 6. 2**

Table of estimated model parameters

$$N_M = \frac{ML}{v} \text{ and } N_K = \frac{K}{Lv} = \frac{\alpha}{L}$$

Sample (ID)	Diameter (inch)	f	N _M	N _K	$\alpha=K/v$ (cm)	1/M (day)
3V	1.5	0.5	0.01	0.31	1.0	0.17
1H	1.5	0.21	2.28	0.01	0.06	0.016
3.5_A	3.5	0.41	0.01	0.31	3.0	2.86
3.5_A(2)	3.5	0.39	0.05	0.23	2.2	1.6
3.5_B	3.5	0.47	0.34	0.183	1.7	2.5
3.5_C	3.5	0.71	0.13	0.19	1.8	6.2

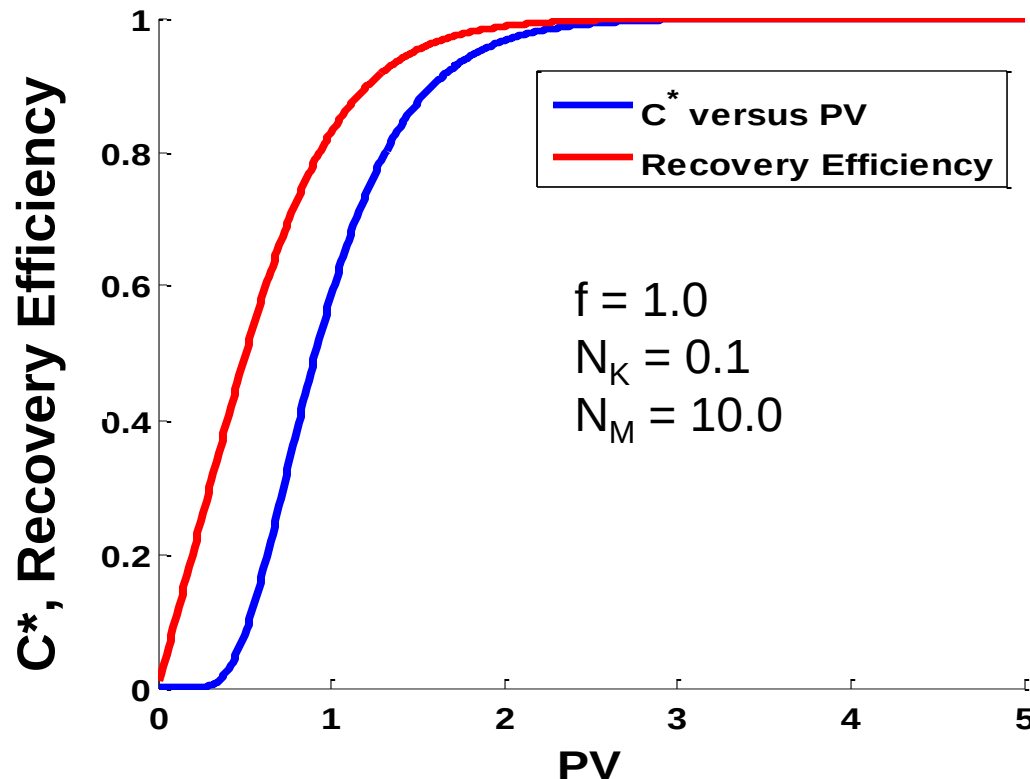


- Flowing fraction is higher for larger diameter cores

- Mass transfer is slow and it would take several days of flood for equilibrium

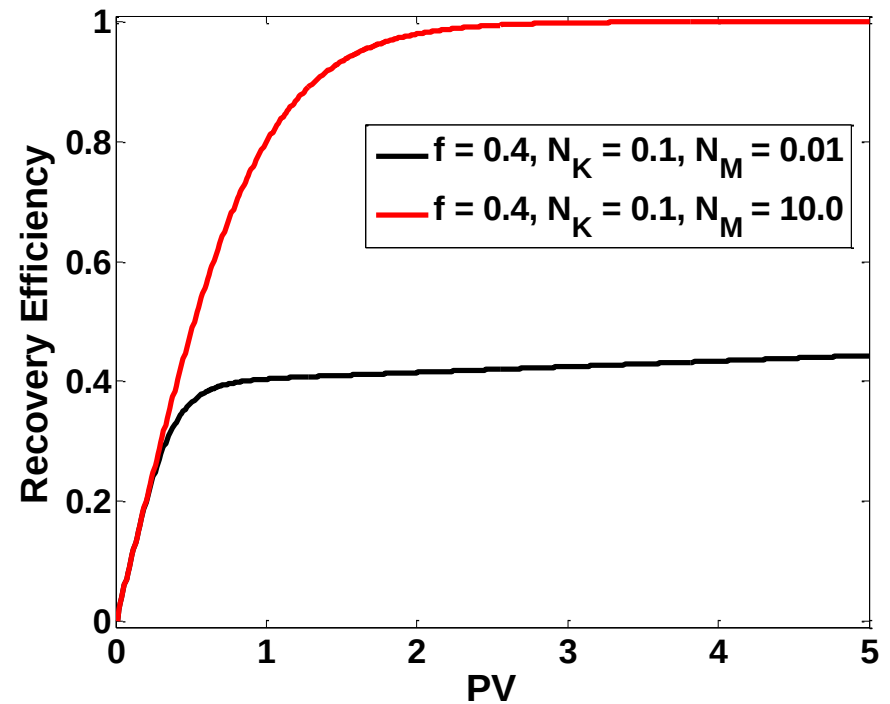
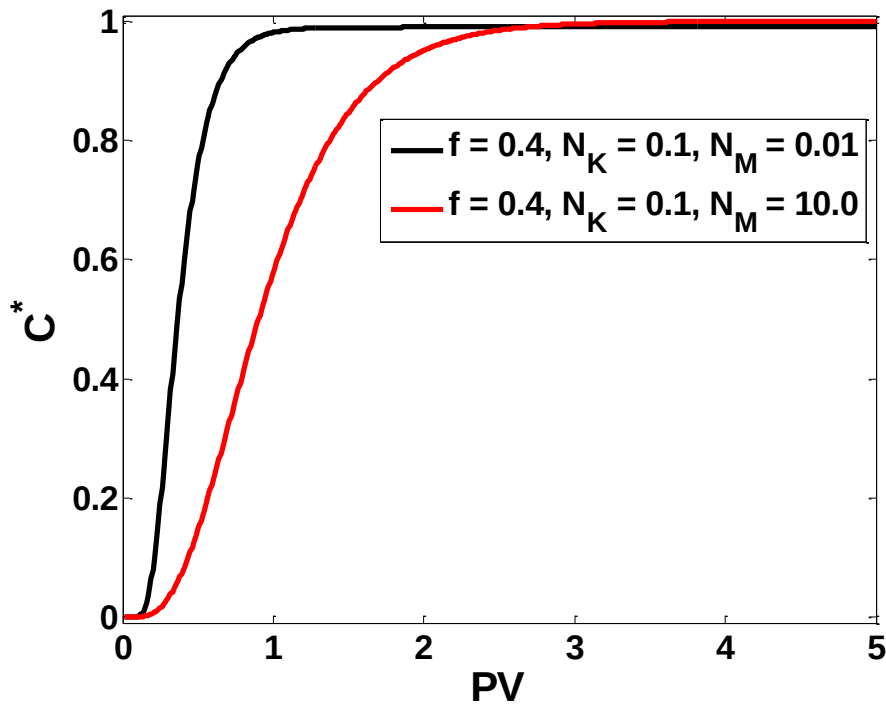
Concept of Recovery Efficiency

- Using synthetic data from Coats Smith model
- 1D system with flowing fraction of 1

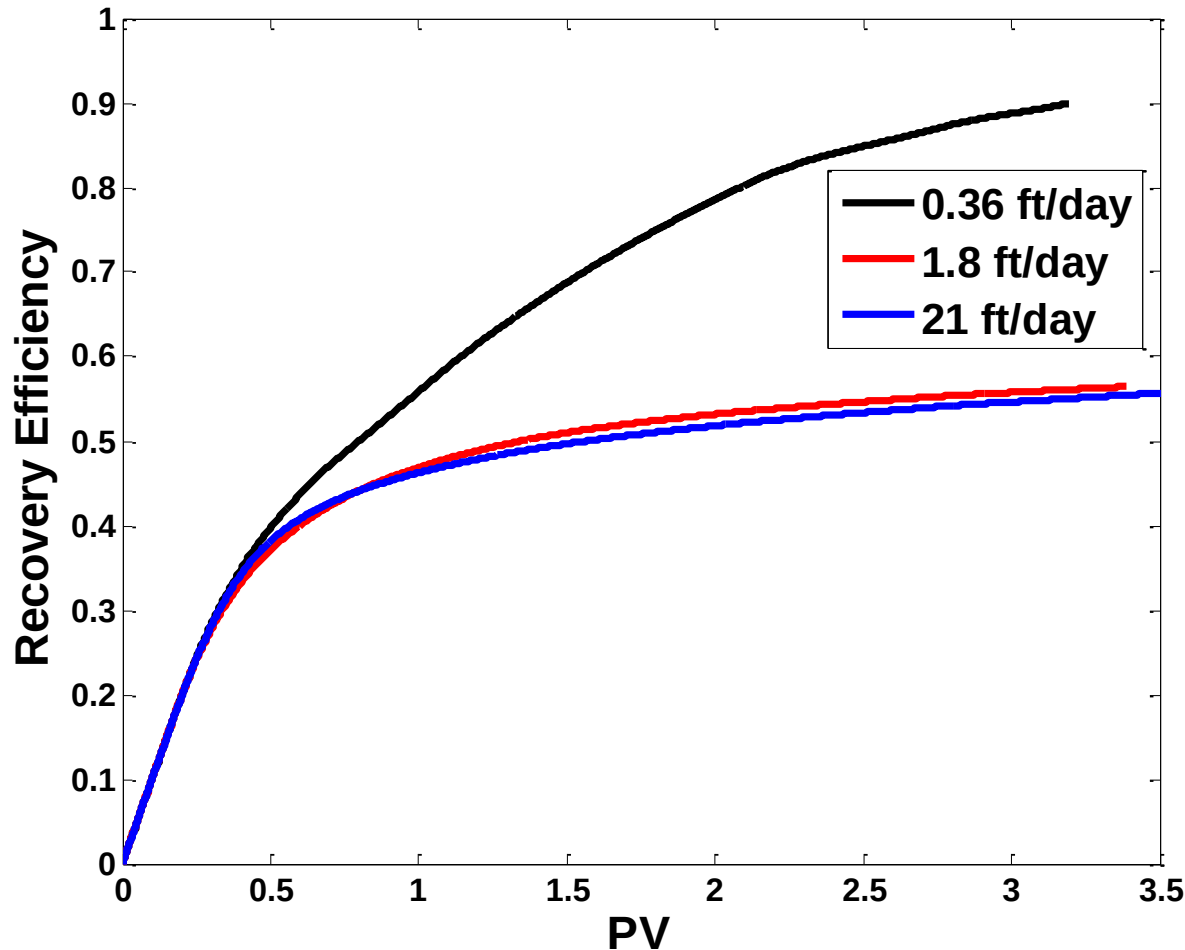


Concept of Recovery Efficiency (contd.)

- Using synthetic data from Coats Smith model
- 1D system with flowing fraction of 0.4



Effect of flowrate on recovery efficiency



Diameter : 3.5 inch

Length = 3.75 inch

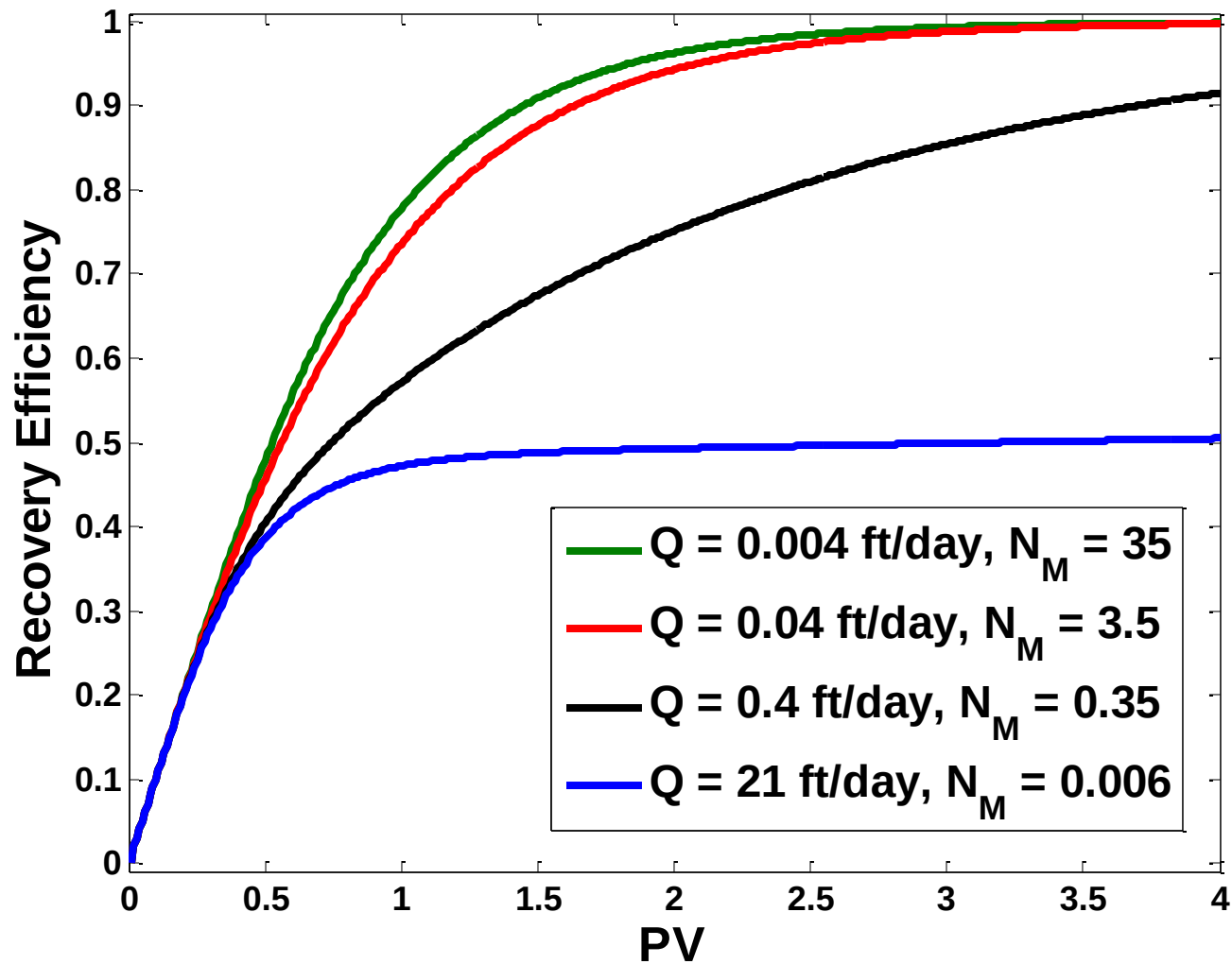
Porosity = 7 %

Permeability = 317 mD

Pore Volume = 41 ml

- **Mass transfer is slow**
- **Dynamic adsorption versus static adsorption**
- **Mobility Ratio = 1**

Dependence of Recovery Efficiency on flow rate



Conclusions

- **NMR measurements show that samples are very heterogeneous. Samples taken within 3 inches of proximity exhibit different T_2 relaxation spectrum.**
- **Permeability is about two orders of magnitude higher for larger diameter (3.5/4.0 inch) diameter samples**
- **Flow experiments on 1.5 inch diameter cores do not suggest the connectivity of vugs**
- **Flowing fraction is higher for larger diameter samples**
- **Small flow rates are necessary to ensure mass transfer between flowing and stationary streams for good recovery efficiency**

Acknowledgements

- **Petróleos Mexicanos (PEMEX)**
- **Consortium for processes in porous media**