

# *Estimation of Flow Geometry, Swept Volume, and Surface Area from Tracer Tests*

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## Outline: Tracers for Estimation of...

- Swept volume
- Flow and storage capacity → Flow Geometry
- Sweep efficiency
- Surface areas for mass and heat transfer

# Swept Volume, Method of Moments (MoM)

Originally developed for closed reactor beds, but generalized to open boundaries, fractured media, multiple wells, multiphase, recycled tracer, ...

$C$  = conservative tracer concentration at a production well

$t^*$  = mean residence time of the tracer

$t_s$  = tracer injection pulse duration

$q$  = volumetric injection/production rate

$m/M$  = fraction of tracer mass recovered

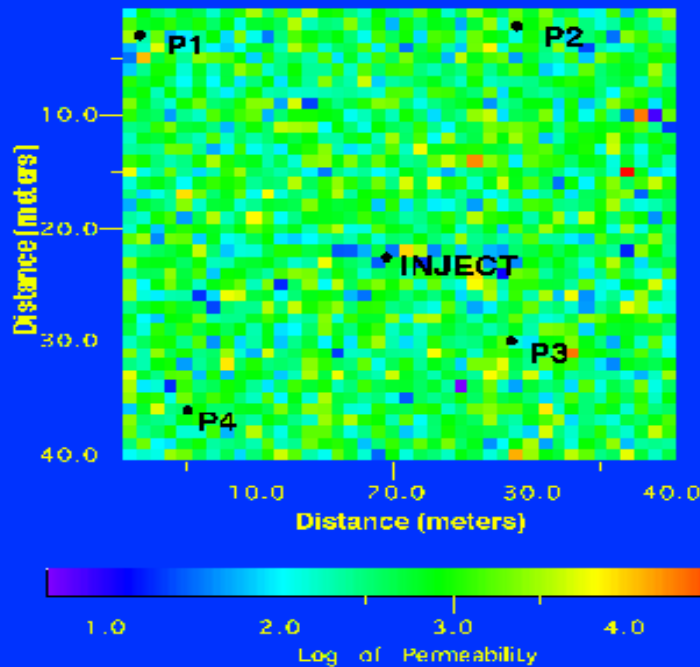
$V_p$  = total pore volume

$$t^* = \frac{\int_0^{\infty} C(t)t dt}{\int_0^{\infty} C(t) dt} - \frac{t_s}{2}$$

First Moment of Tracer Response - First Moment of Injection Pulse

$$V_p = q \cdot \frac{m}{M} \cdot t^*$$

## Example of Moment Calculations (Shook, 1998)



***Permeability Field and Well Locations  
for Example Problem***

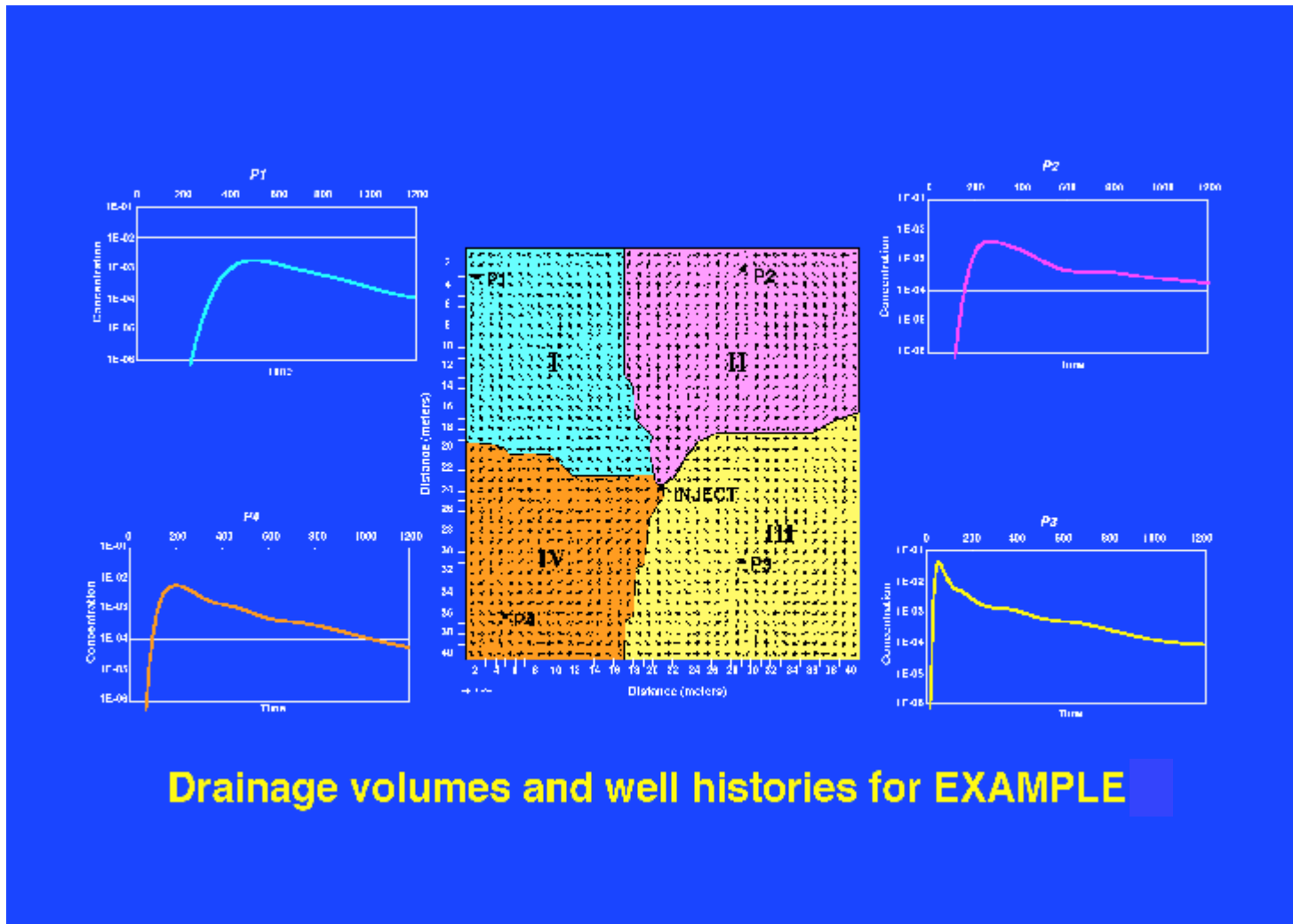
Generate random perm field, simulate tracer test

Interpret tracer histories using MoM

Determine fluid velocities in simulation, and determine volumes drained by each production well

Compare estimates: MoM vs. velocity field

**Example of MoM Calculation (Shook, 1998). Outer curves are the tracer histories at each production well. Inner figure shows unit velocity vectors and drainage volume estimates.**



## MoM Analysis Results

<i>Well #</i>	<i>Vp from MoM</i>	<i>Vp from velocity</i>	<i>Error</i>
<i>I</i>	<i>2267 m<sub>3</sub></i>	<i>2260 m<sub>3</sub></i>	<i>0.30%</i>
<i>II</i>	<i>2902 m<sub>3</sub></i>	<i>3007 m<sub>3</sub></i>	<i>3.50%</i>
<i>III</i>	<i>2618 m<sub>3</sub></i>	<i>2550 m<sub>3</sub></i>	<i>2.70%</i>
<i>IV</i>	<u><i>2140 m<sub>3</sub></i></u>	<u><i>2180 m<sub>3</sub></i></u>	<i>1.80%</i>
<i>Total</i>	<i>9929 m<sub>3</sub></i>	<i>10000 m<sub>3</sub></i>	<i>0.70%</i>

- Method of Moments (MoM) gives excellent approximations to drainage volumes.
- Method is simple to use, very robust.

# Flow Capacity, Storage Capacity, and $F-\Phi$ Curves

## Definitions

- **Flow Capacity,  $F$ : Fraction of total flow in a given streamline (flow pathway)**
- **Storage Capacity,  $\Phi$ : Fraction of total pore volume in a given streamline (flow pathway)**
- **$F-\Phi$  curve: a CDF of Flow Capacity – Storage Capacity (i.e., Flow Geometry)**

# F and $\Phi$ Working equations...

## ■ Flow Capacity, F:

A running sum (CDF) of the volumetric flow of the “fastest” fractures

$$F_{\ell} = \frac{\sum_{i=1}^{\ell} q_i}{q_T} \cong \frac{\int_0^t c d\tau}{\int_0^{\infty} c dt} = F(t)$$

Fraction of volumetric flow (t)

## ■ Storage Capacity, $\Phi$ :

A running sum of the pore volume of the fastest fractures

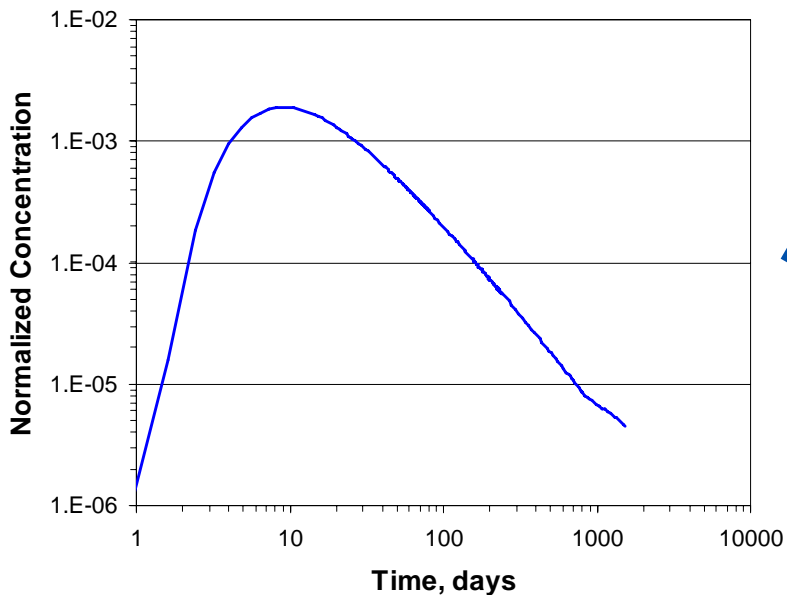
$$\Phi_{\ell} = \frac{\sum_{i=1}^{\ell} V_{pi}}{\sum_{j=1}^{\infty} V_{pj}} \cong \frac{\int_0^t c \tau d\tau}{\int_0^{\infty} c t dt} = \Phi(t)$$

Fraction of flowing volume (t)



# F- $\Phi$ curve for Beowawe geothermal field

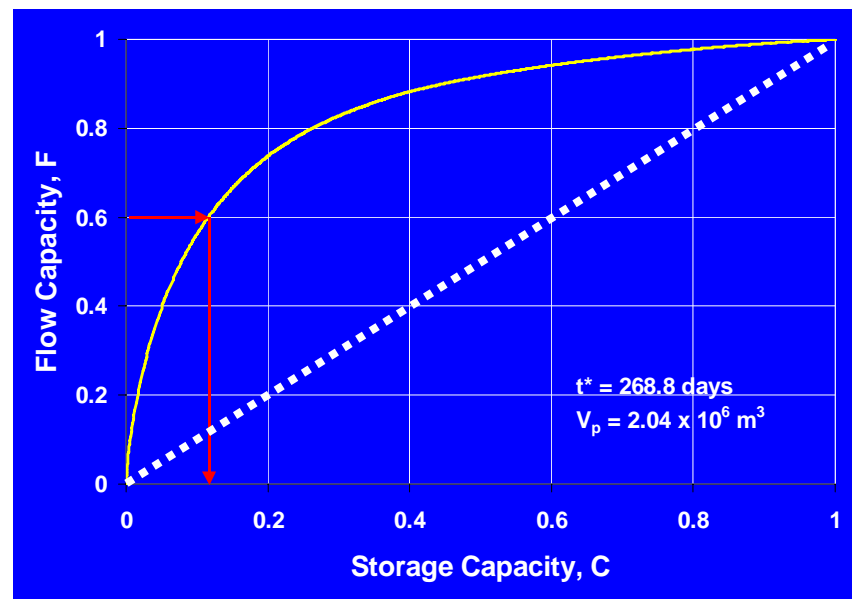
Tracer Breakthrough Curve (smoothed)



Interpretation: 60% of the flow occurs in 12% of the pore volume



F- $\Phi$  Curve

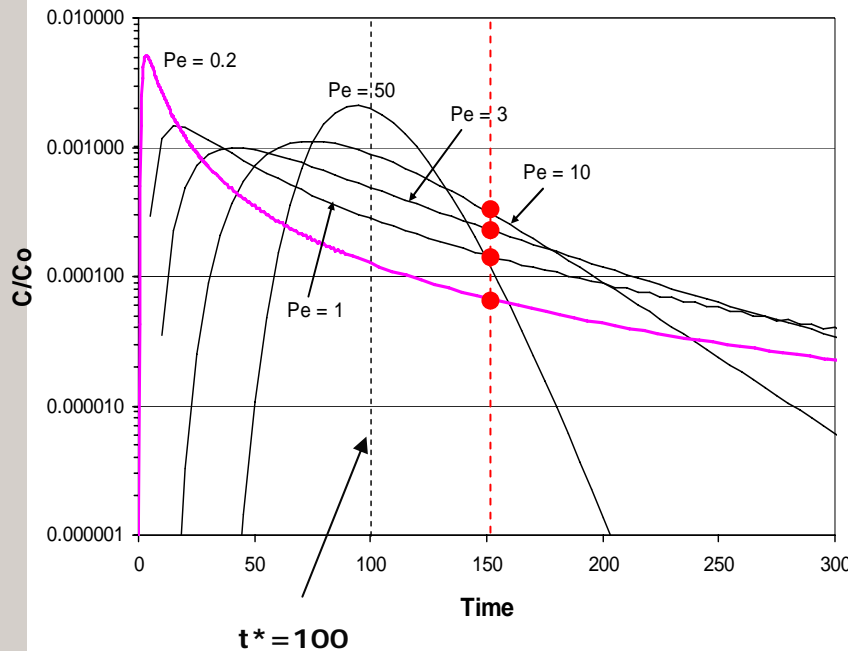


# Petroleum Engineering → Hydrology: F-Φ and Peclet Number as Similar Measures of Flow Geometry

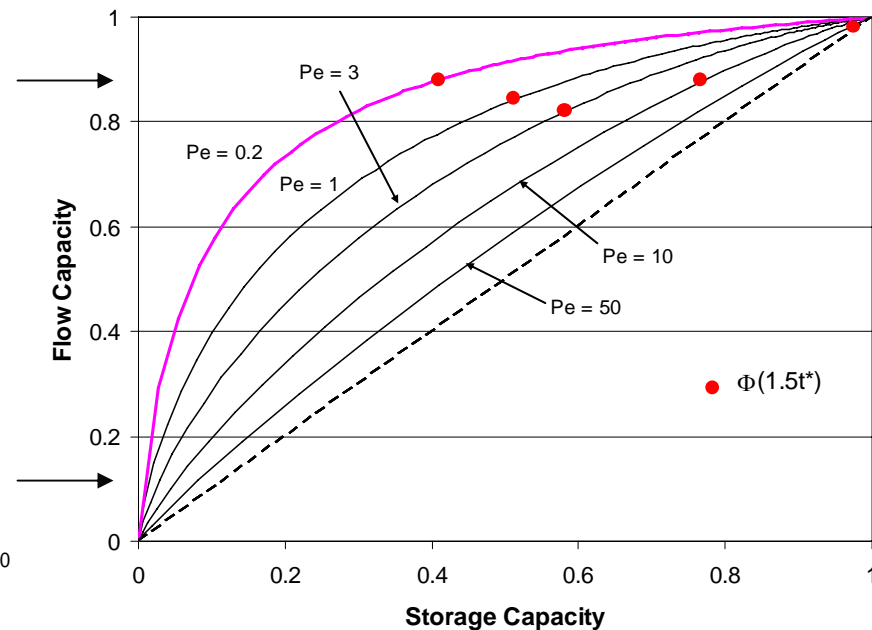
Peclet Number,  $Pe = L/\alpha$   
 $L$  = well separation, m  
 $\alpha$  = dispersivity, m

F-Φ more general; not  
 limited to classic advection-  
 dispersion equation behavior  
 (i.e., Fickian dispersion)

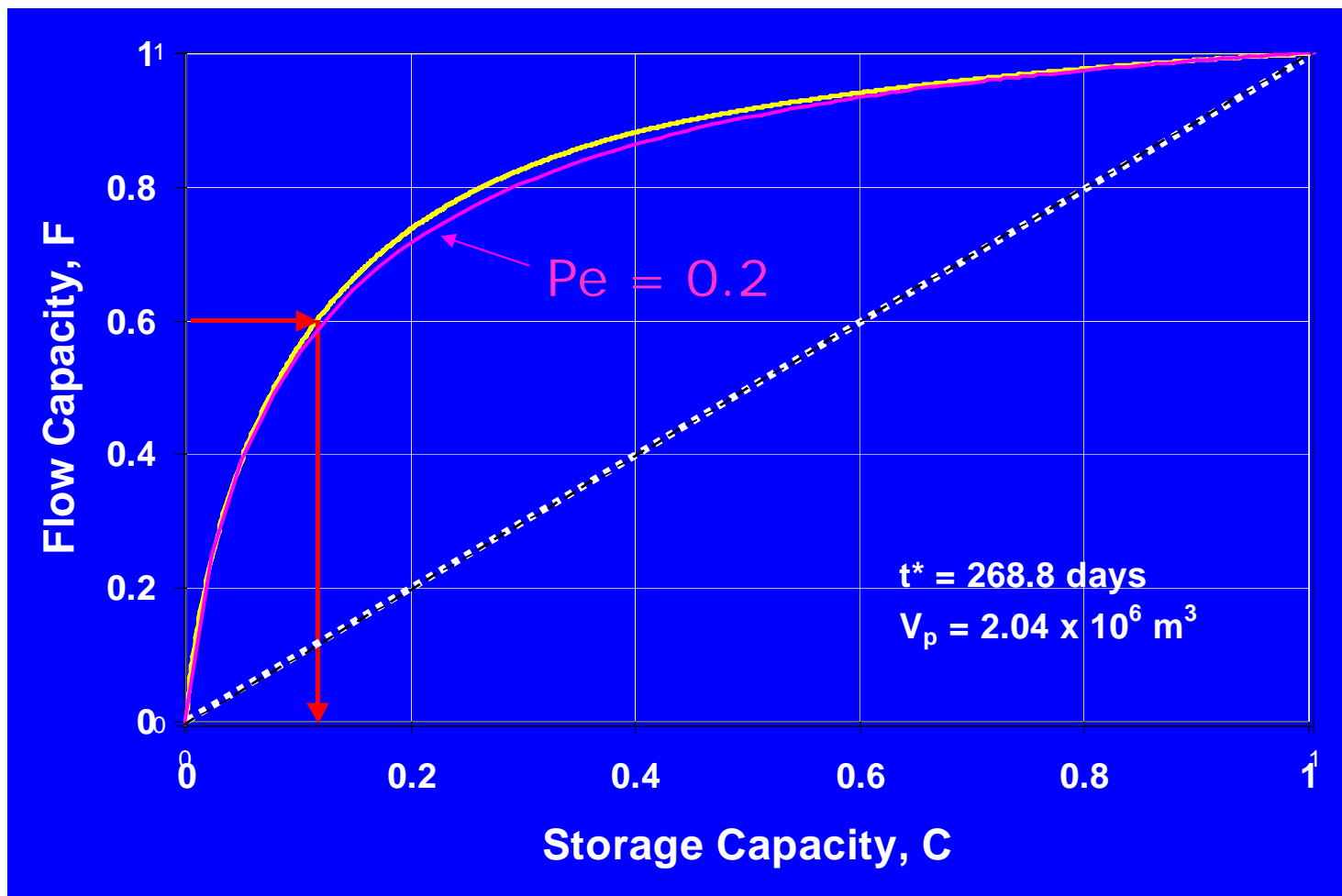
Tracer Breakthrough Curves



Corresponding F-Φ Curves



# Peclet number for Beowawe geothermal field

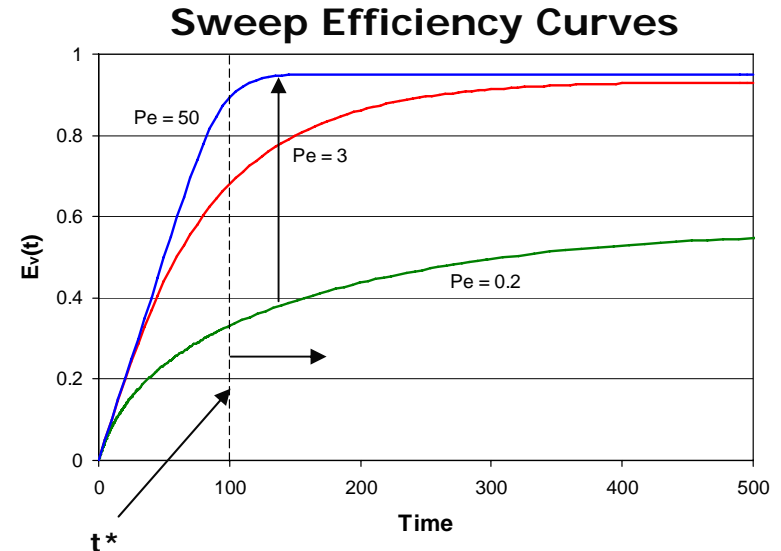
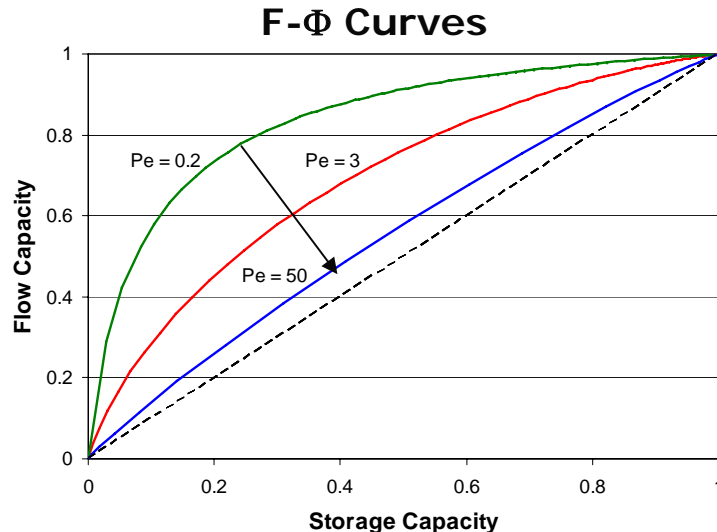


# Using F- $\Phi$ curves: Sweep Efficiency

- Use F- $\Phi$  to calculate sweep efficiency,  $E_v(t)$ :

$$E_v(t) = \frac{V_{swept}(t)}{V_p} = \frac{q \int_0^t (1 - F(\tau)) d\tau}{V_p}$$

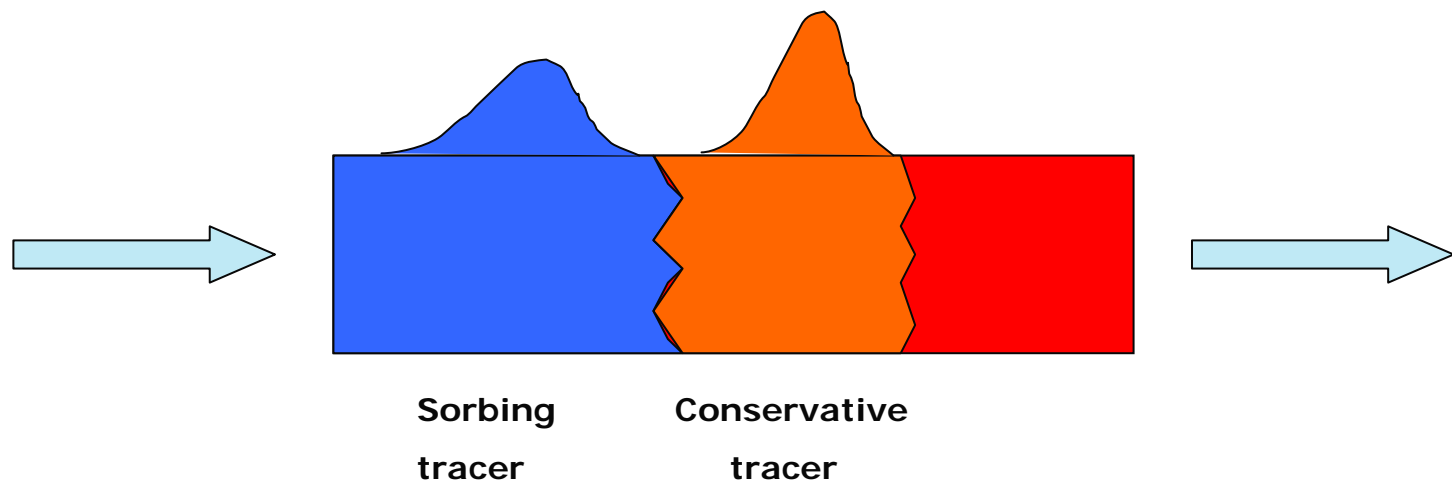
- Challenge in reservoir management is to maximize  $V_{swept}(t) = V_p E_v(t)$  via manipulation of  $V_p$  and  $E_v(t)$
- Do this by adjusting  $q_{inj,i}$  and  $q_{prod,j}$  and/or by altering reservoir flow geometry via expansion or additives



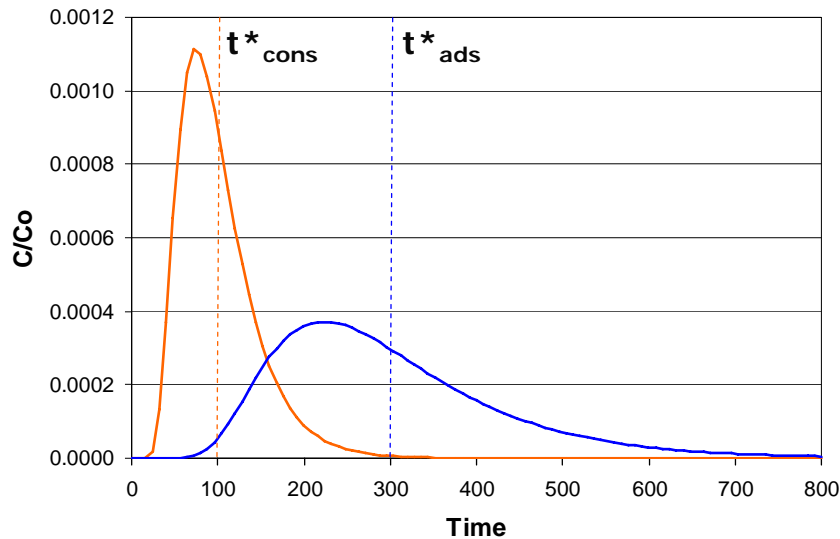
## Surface Area from Adsorbing Tracers

In any given fracture/flow pathway, a sorbing tracer is retarded compared to a conservative tracer

By measuring the adsorption isotherm of a tracer on rock and calculating mean residence times of conservative and adsorbing tracers, we can estimate surface area



# Surface Area Estimation



$$R_f = t^*_{ads} / t^*_{cons}$$

$$R_f = 1 + K_a A / V_p$$

$R_f$  = retardation factor

$K_a$  = tracer partition coefficient,  $m^3/m^2$

$A$  = surface area,  $m^2$

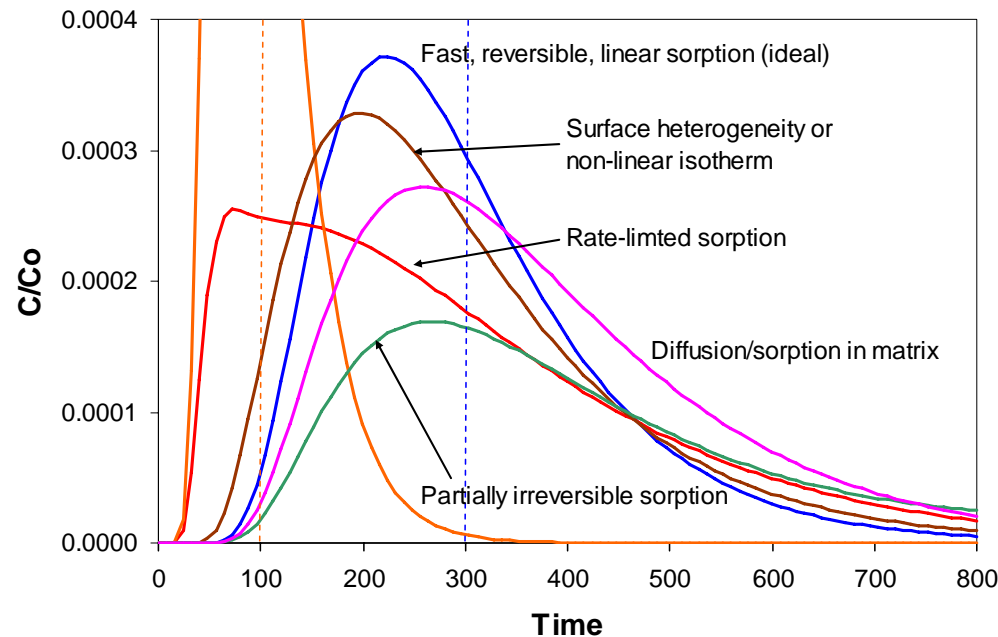
$V_p$  = swept volume,  $m^3$

- Measure tracer partition coefficient,  $K_a$ , in laboratory experiments
- Determine swept volume,  $V_p$ , from  $t^*_{cons}$
- Determine  $t^*_{ads}$  from adsorbing tracer breakthrough curve and calculate  $A$  from:

$$A = \left( \frac{t^*_{ads}}{t^*_{cons}} - 1 \right) \frac{V_p}{K_a} = (R_f - 1) \frac{V_p}{K_a}$$

# Surface Area - Potential Complications

- Rate-limited sorption/desorption (kinetic effects)
- Irreversible or slow sorption
- Non-linear sorption isotherm
- Diffusion into and sorption in matrix pores
- Heterogeneity in surface mineralogy and thus in  $K_a$  values



## Summary

- Conservative tracers provide estimates of swept volume and sweep efficiency via  $F-\Phi$  curves
- Allows informed operational adjustments to increase swept volume and sweep efficiency - use tracers again to assess adjustments
- Adsorbing tracers have potential to provide surface area estimates for mass and heat transfer applications (e.g., oil shale extraction, geothermal heat extraction)
  - Identifying appropriate adsorbing tracers and accounting for adsorption non-idealities is a challenge