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, ...

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

First Moment of Tracer Response − First Moment of Injection Pulse

C = <u>conservative</u> tracer concentration at a production well

t^* = mean residence time of the tracer

t_s = tracer injection pulse duration

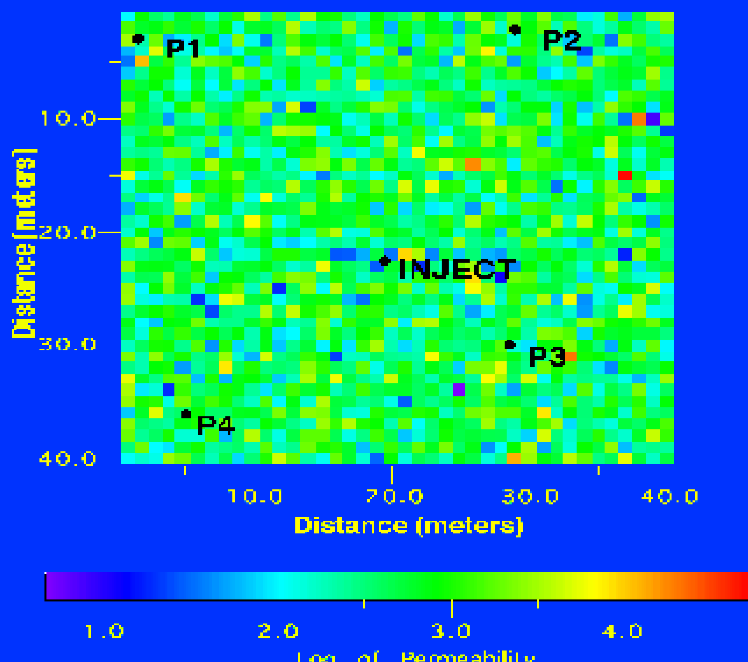
q = volumetric injection/production rate

m/M = fraction of tracer mass recovered

V_p = total pore volume

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

Example of Moment Calculations (Shook, 1998)



Permeability Field and Well Locations for Example Problem

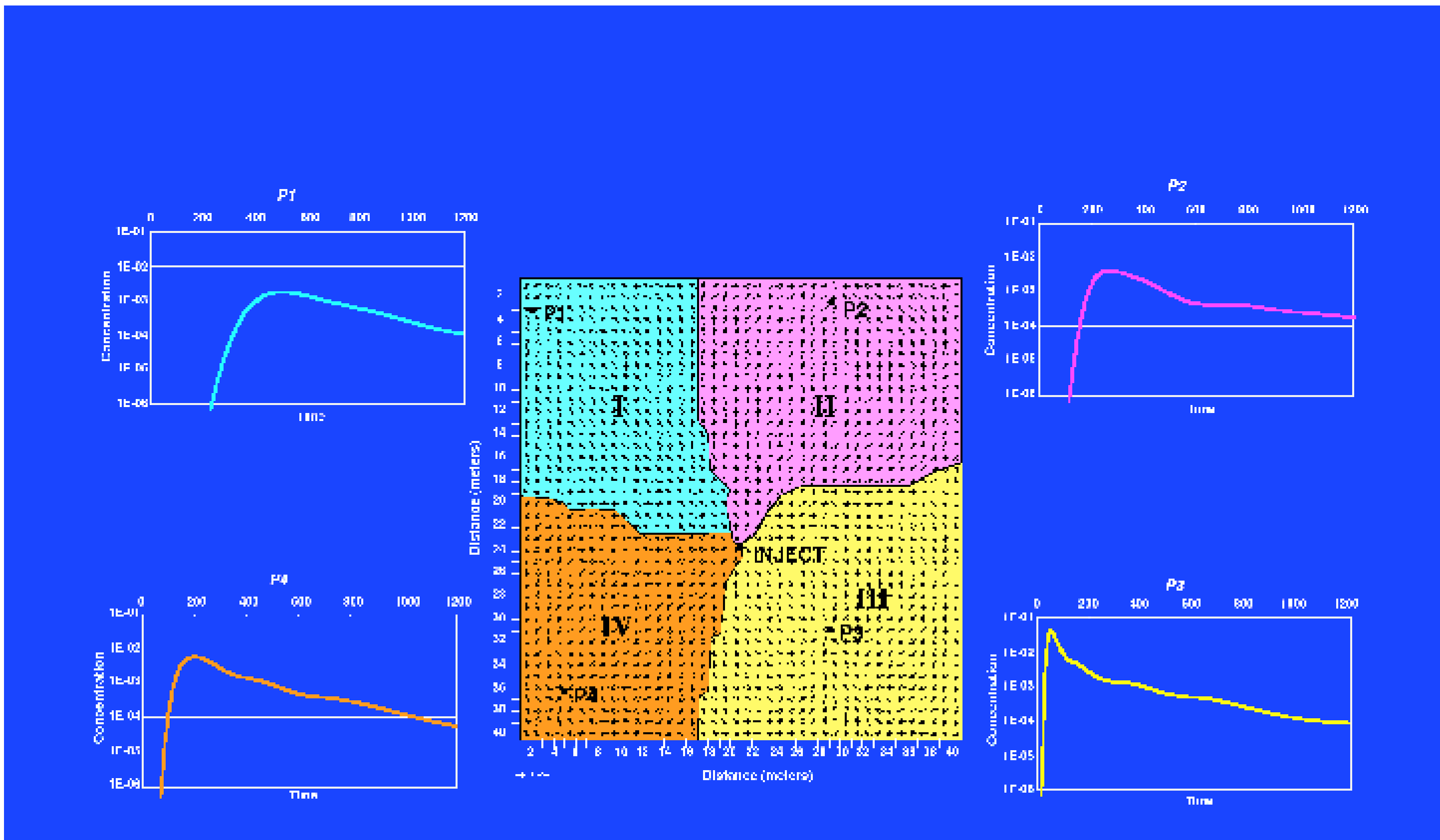
Generate random perm field, simulate tracer test

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.



Drainage volumes and well histories for EXAMPLE

MoM Analysis Results

Well #	Vp from MoM	Vp from velocity	Error
I	*2267 m^3*	*2260 m^3*	*0.30%*
II	*2902 m^3*	*3007 m^3*	*3.50%*
III	*2618 m^3*	*2550 m^3*	*2.70%*
IV	*2140 m^3*	*2180 m^3*	*1.80%*
Total	*9929 m^3*	*10000 m^3*	*0.70%*

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

Flow Capacity, Storage Capacity, and F-Φ Curves

Definitions

- **Flow Capacity, F: Fraction of total flow in a given streamline (flow pathway)**

- **Storage Capacity, Φ: Fraction of total pore volume in a given streamline (flow pathway)**

- **F-Φ curve: a CDF of Flow Capacity – Storage Capacity (i.e., Flow Geometry)**

F and Φ 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, Φ:**

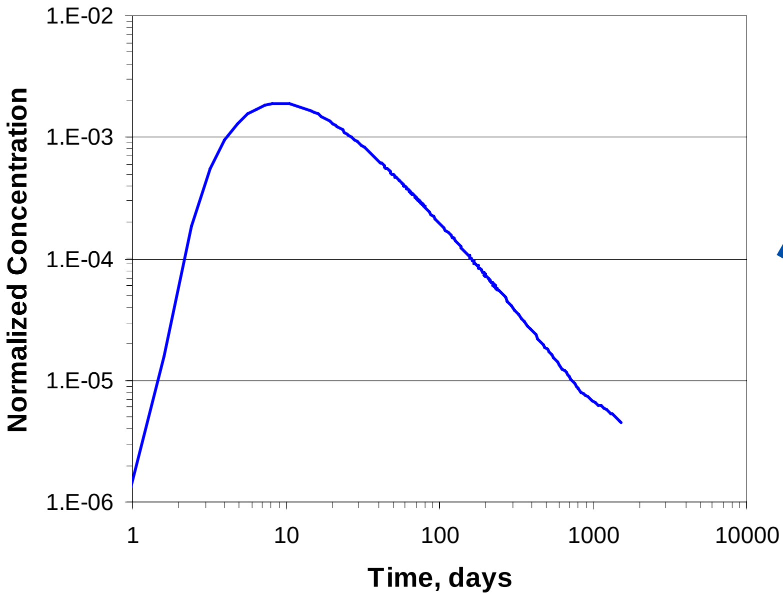
  A running sum of the pore volume of the fastest fractures

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

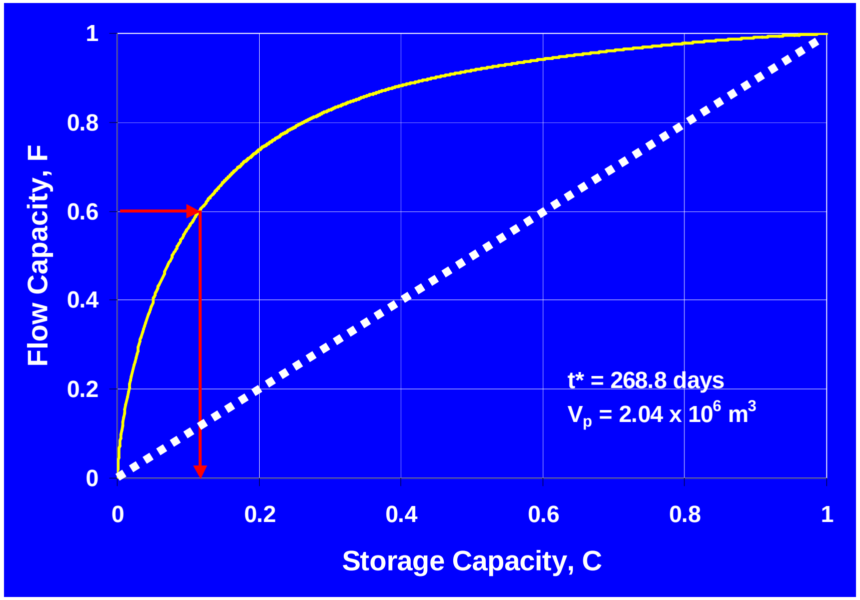
Fraction of flowing volume (t)

F-Φ curve for Beowawe geothermal field

Tracer Breakthrough Curve (smoothed)



F-Φ Curve



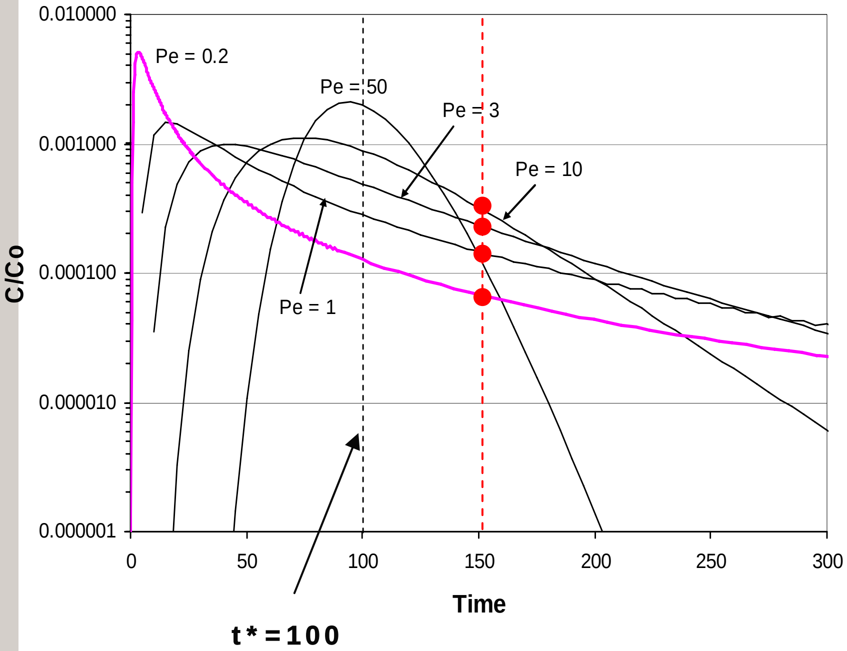
Interpretation: 60% of the flow occurs in 12% of the pore volume

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

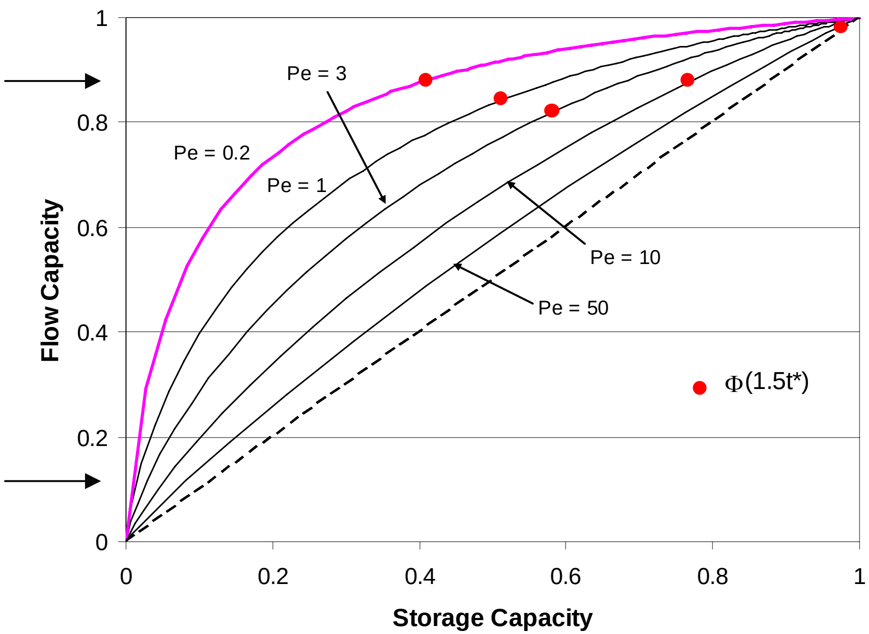
Peclet Number, Pe = L / α
L = well separation, m
α = dispersivity, m

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

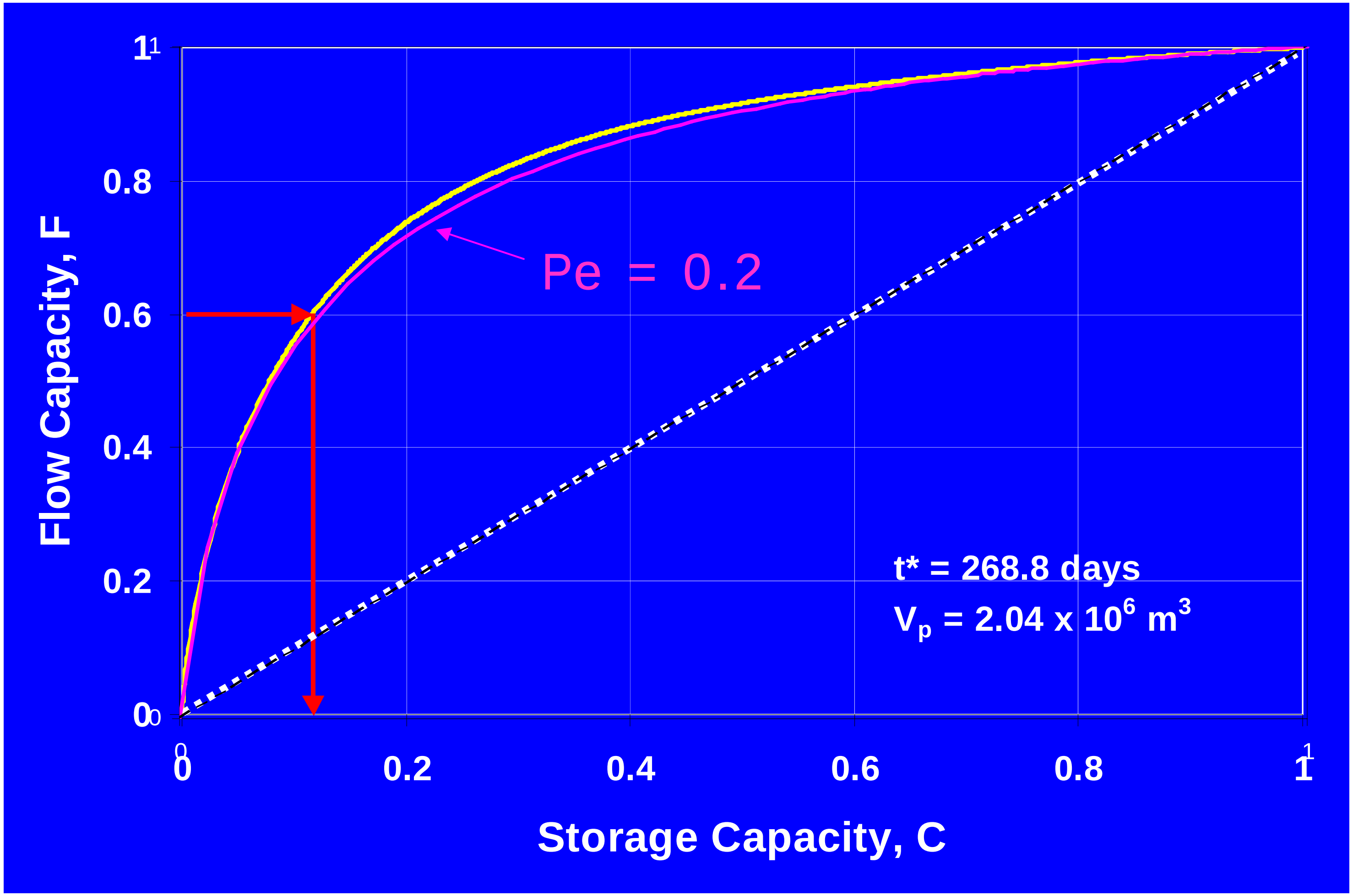
Tracer Breakthrough Curves



Corresponding F-Φ Curves

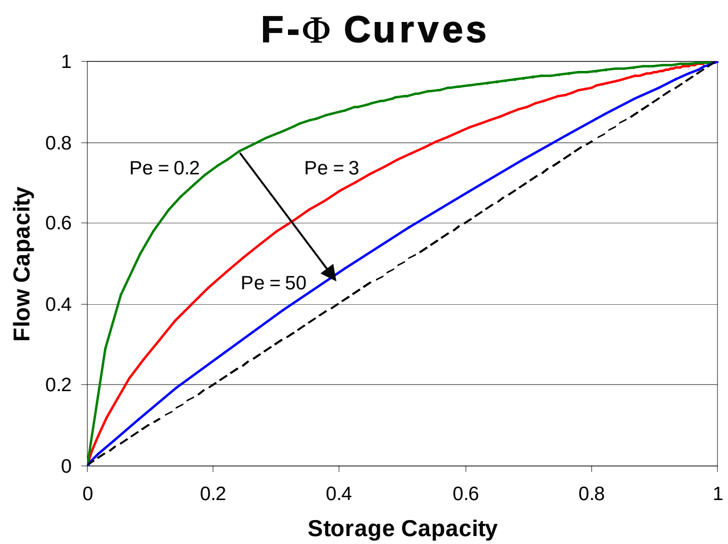


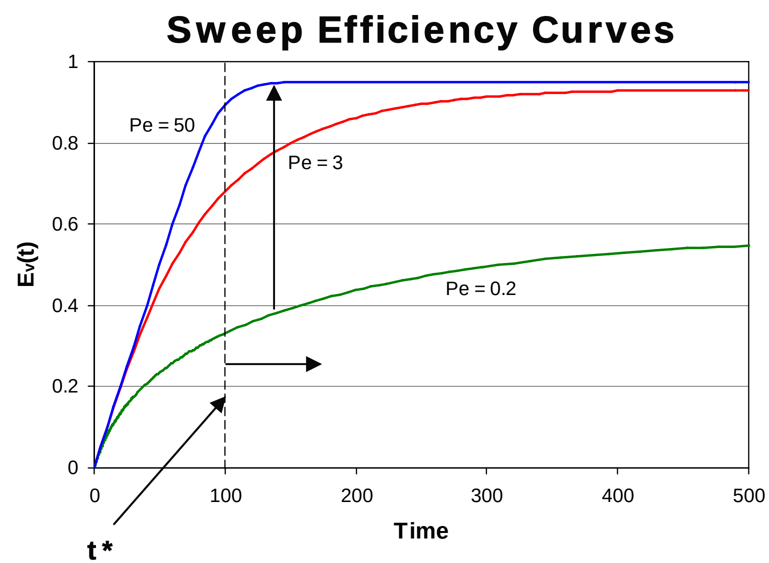
Peclet number for Beowawe geothermal field



Using F-Φ curves: Sweep Efficiency

- Use F-Φ 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

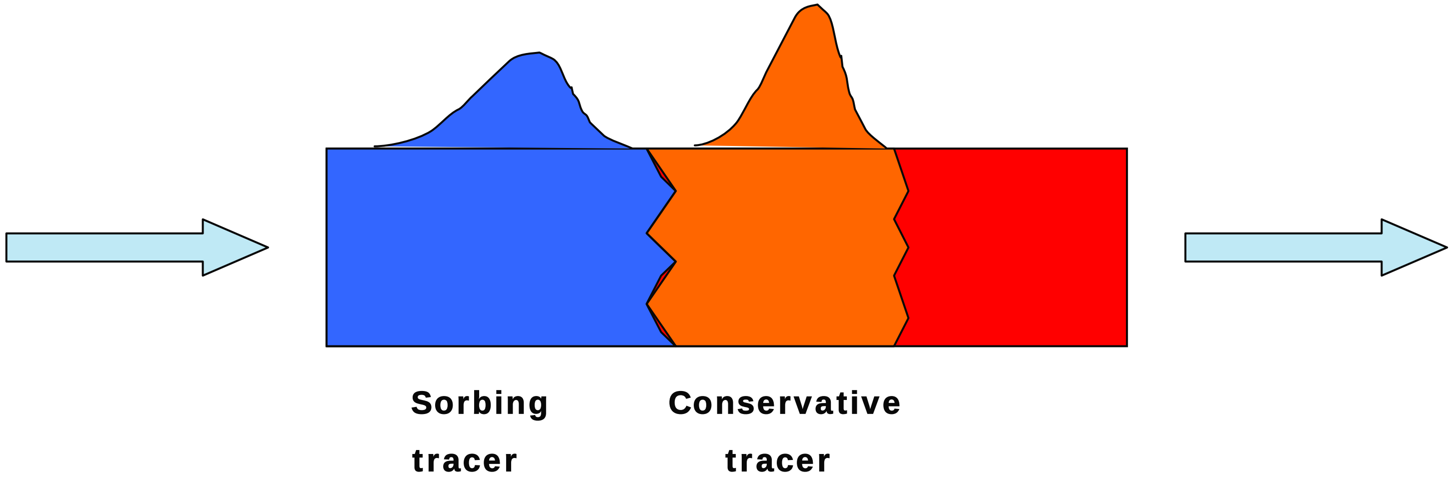




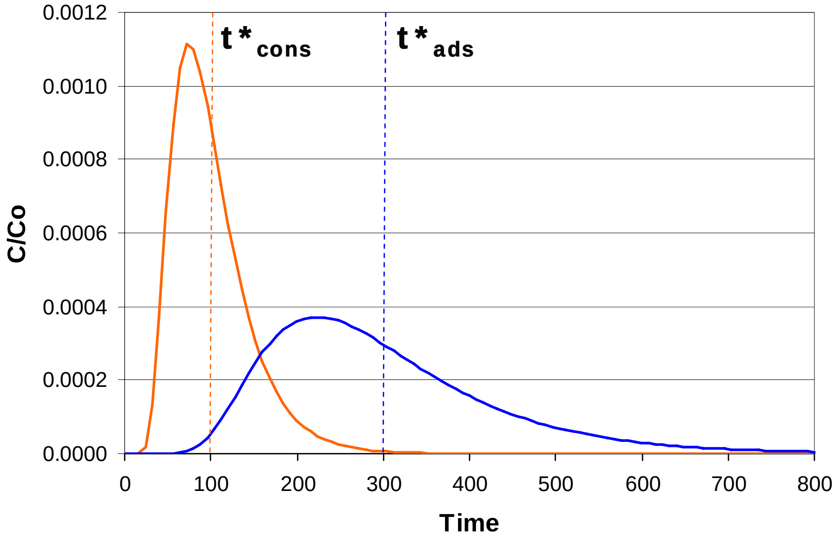
Surface Area from Adsorbing Tracers

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



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

$R_f = 1+K_aA/V_p$

R_f = retardation factor

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

A = surface area, m^2

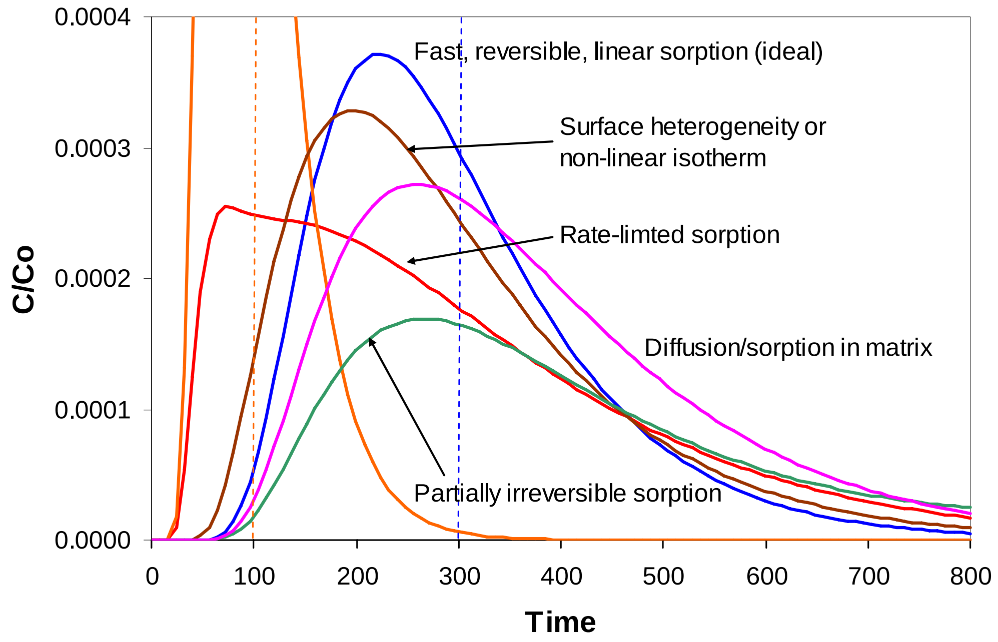
V_p = swept volume, m^3

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

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

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
- Hetereogeneity in surface mineralogy and thus in K_a values



Summary

- Conservative tracers provide estimates of swept volume and sweep efficiency via F-Φ 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