Influences of Flow Transients and Porous-Medium Heterogeneity On Colloid-Associated Contaminant Transport in the Vadose Zone

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Objective

Provide new knowledge needed to assess and control the movement of colloid-associated contaminants at DOE sites.

Research Questions

- **What mechanisms govern colloid mobilization and deposition within unsaturated porous media?**
- **What role does vadose-zone heterogeneity have in colloid transport and colloid-associated radionuclide transport?**
- **Can published models that describe colloid-facilitated transport in water-saturated porous media be adapted for the vadose zone?**

Task #1: Characterizing colloid mobilization and deposition in unsaturated porous media

Approach

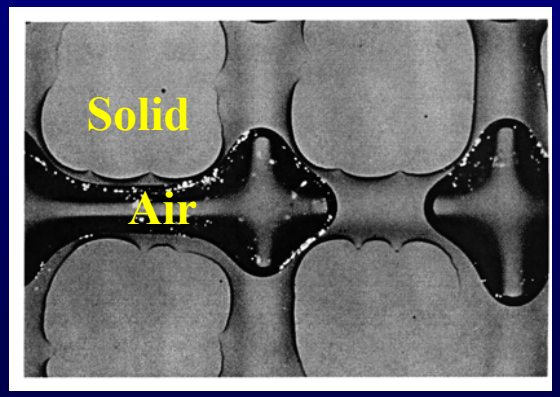
- Measure colloid transport and mass transfer in laboratory columns

Colloids: silica and illite

Porous media: "ideal" and intact cores

Flow regime: steady and transient

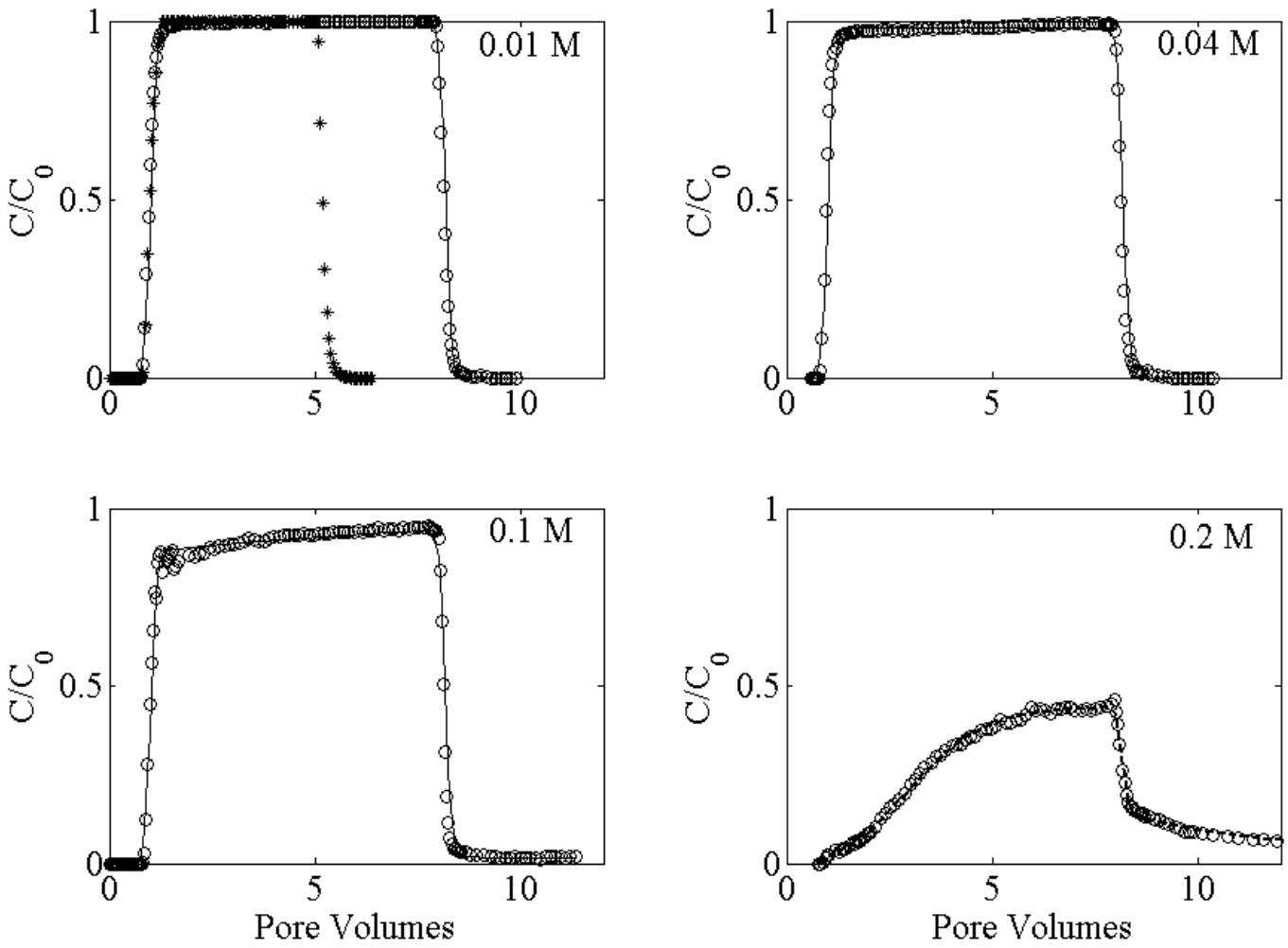
- Identify mechanisms of mobilization in micromodel experiments



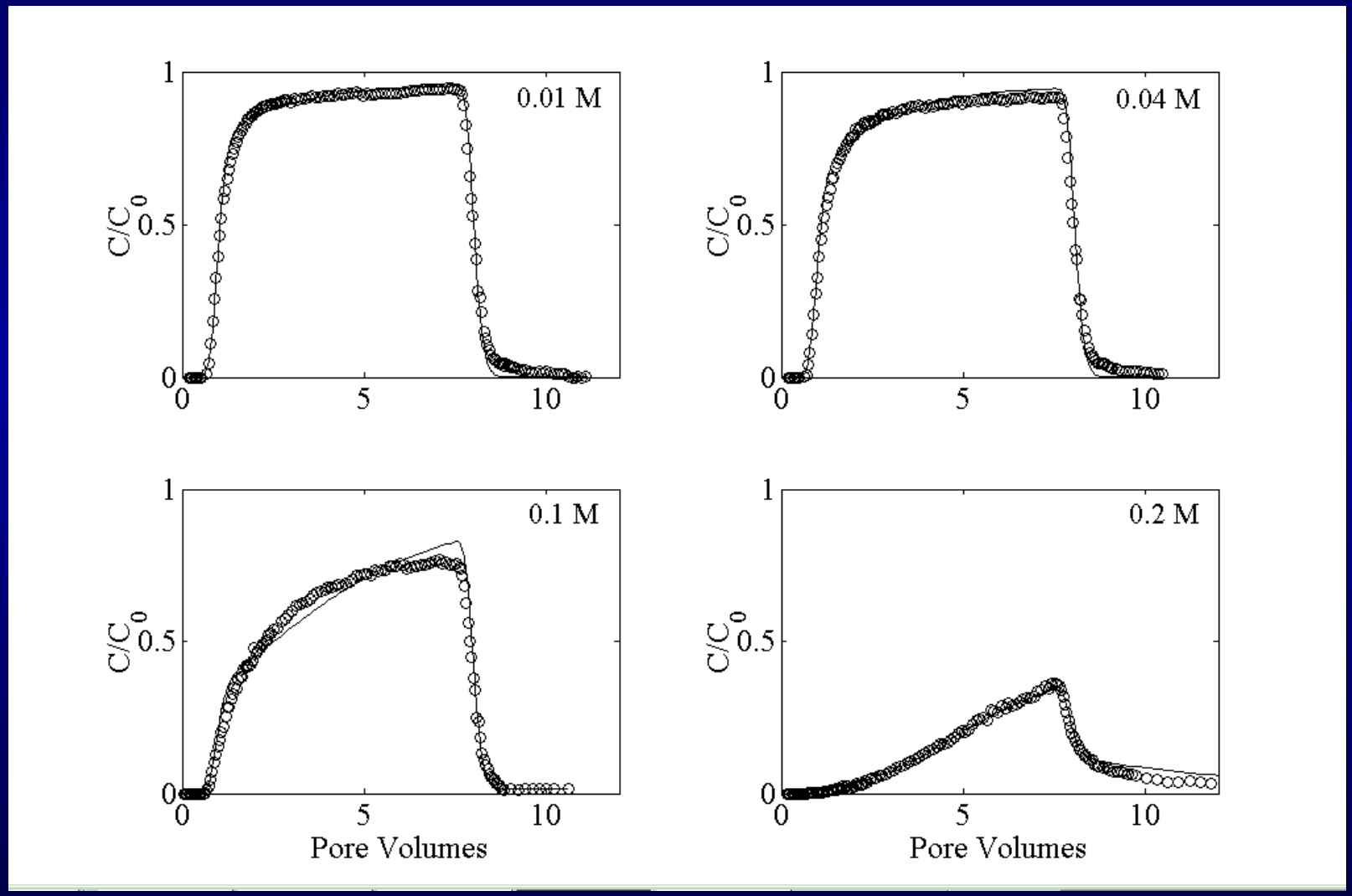
Wan and Wilson, 1994

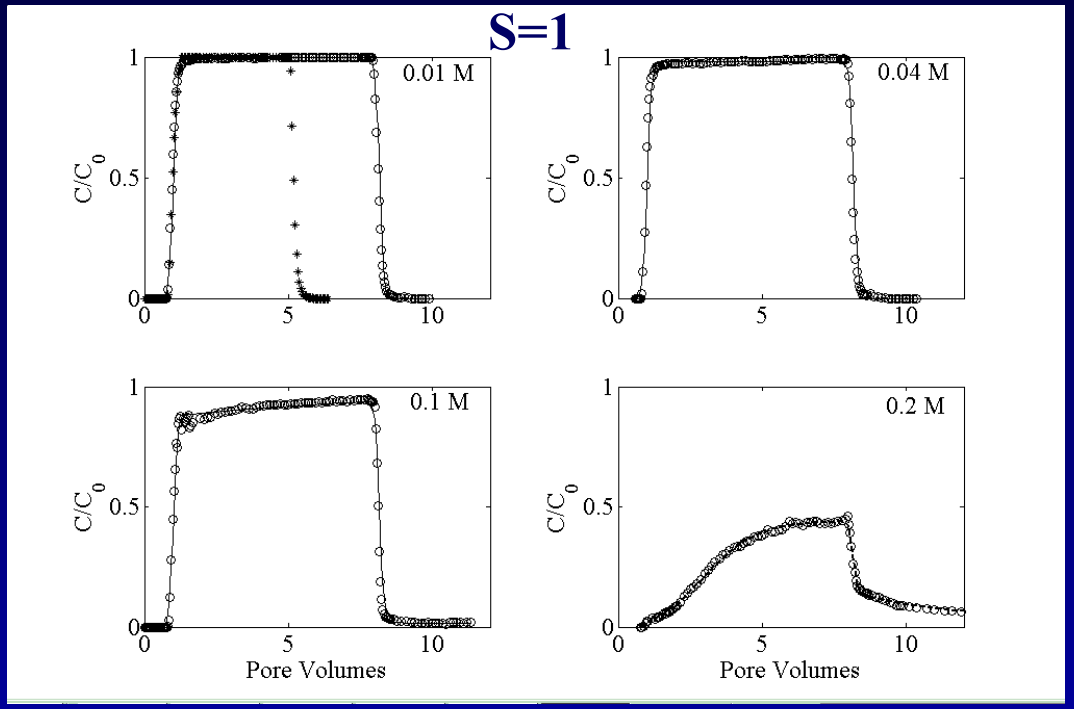
Focus on flow transients

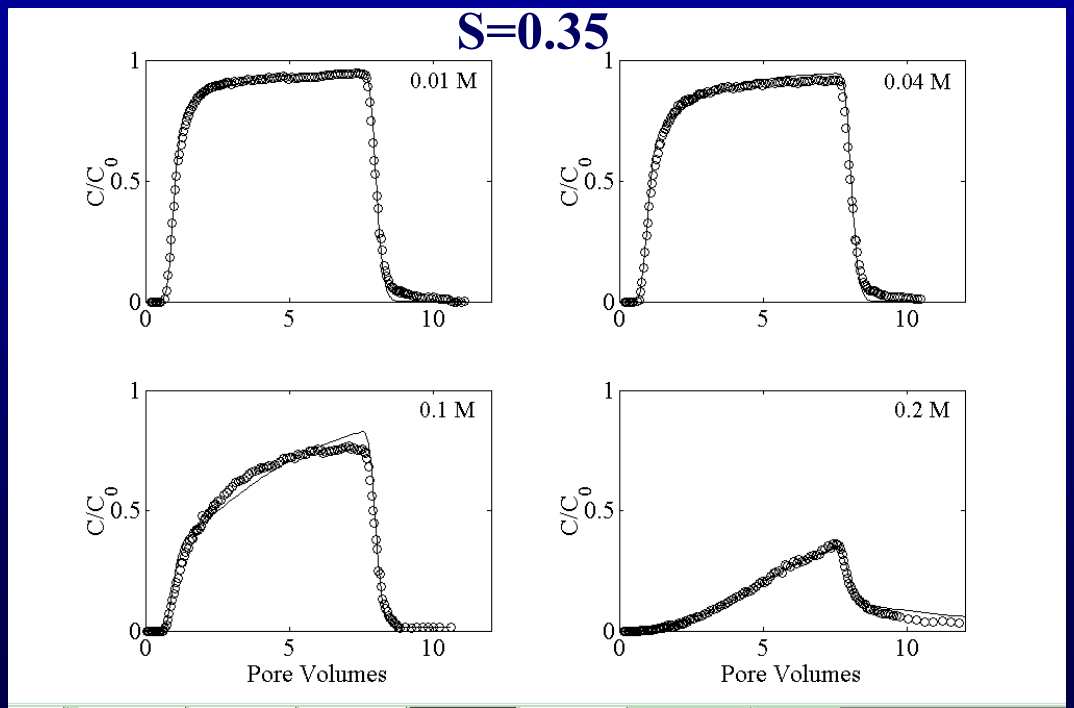
Ionic-Strength Effects on Silica-Colloid Transport in Saturated Media (S = 1)



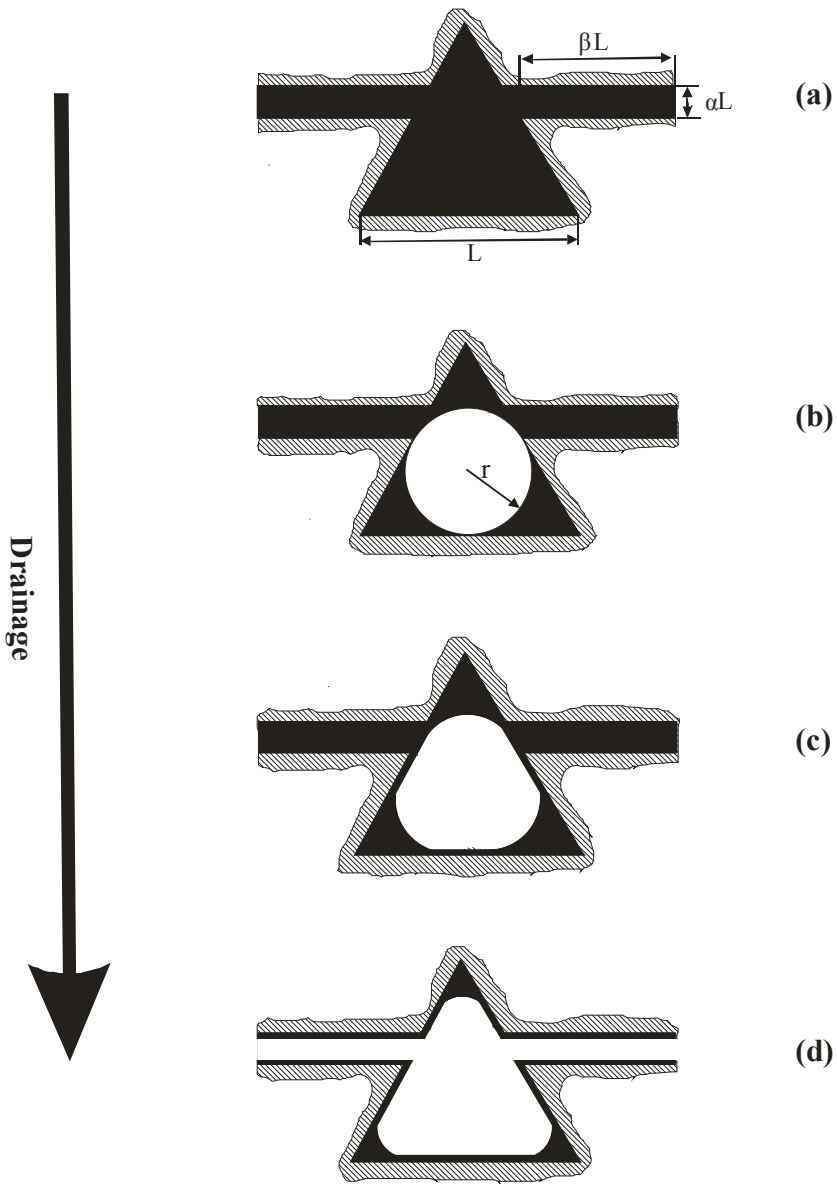
Ionic-Strength Effects on Silica-Colloid Transport in Unsaturated Media (S = 0.35)



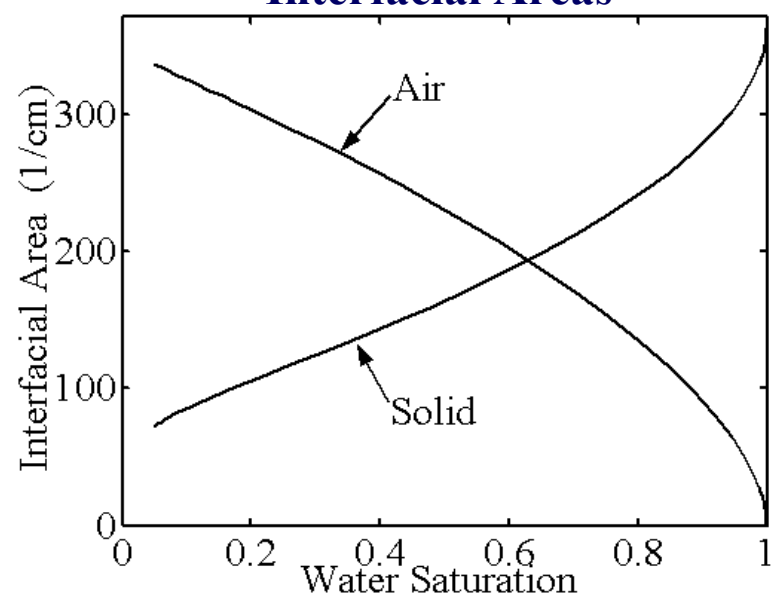

S=1
0.01 M
0.04 M
0.1 M
0.2 M
C/C0
Pore Volumes


S=0.35
0.01 M
0.04 M
0.1 M
0.2 M
C/C0
Pore Volumes

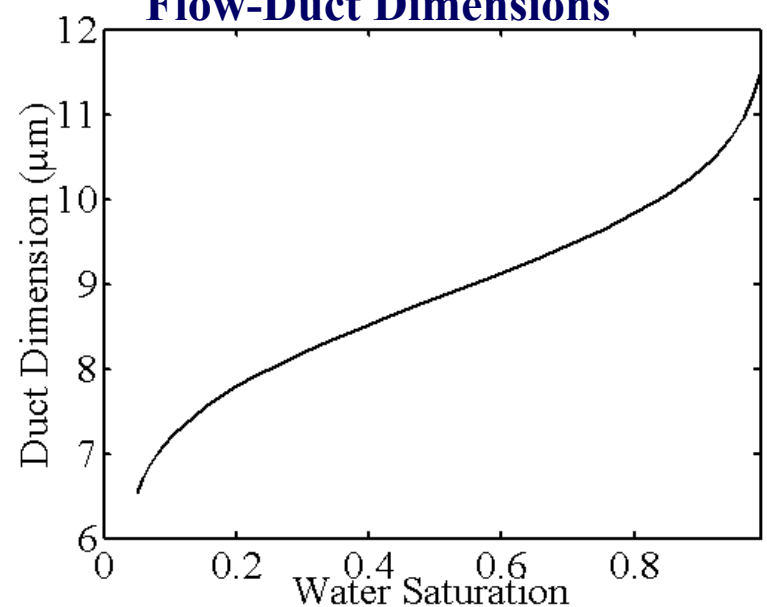
Pore Drainage



Interfacial Areas

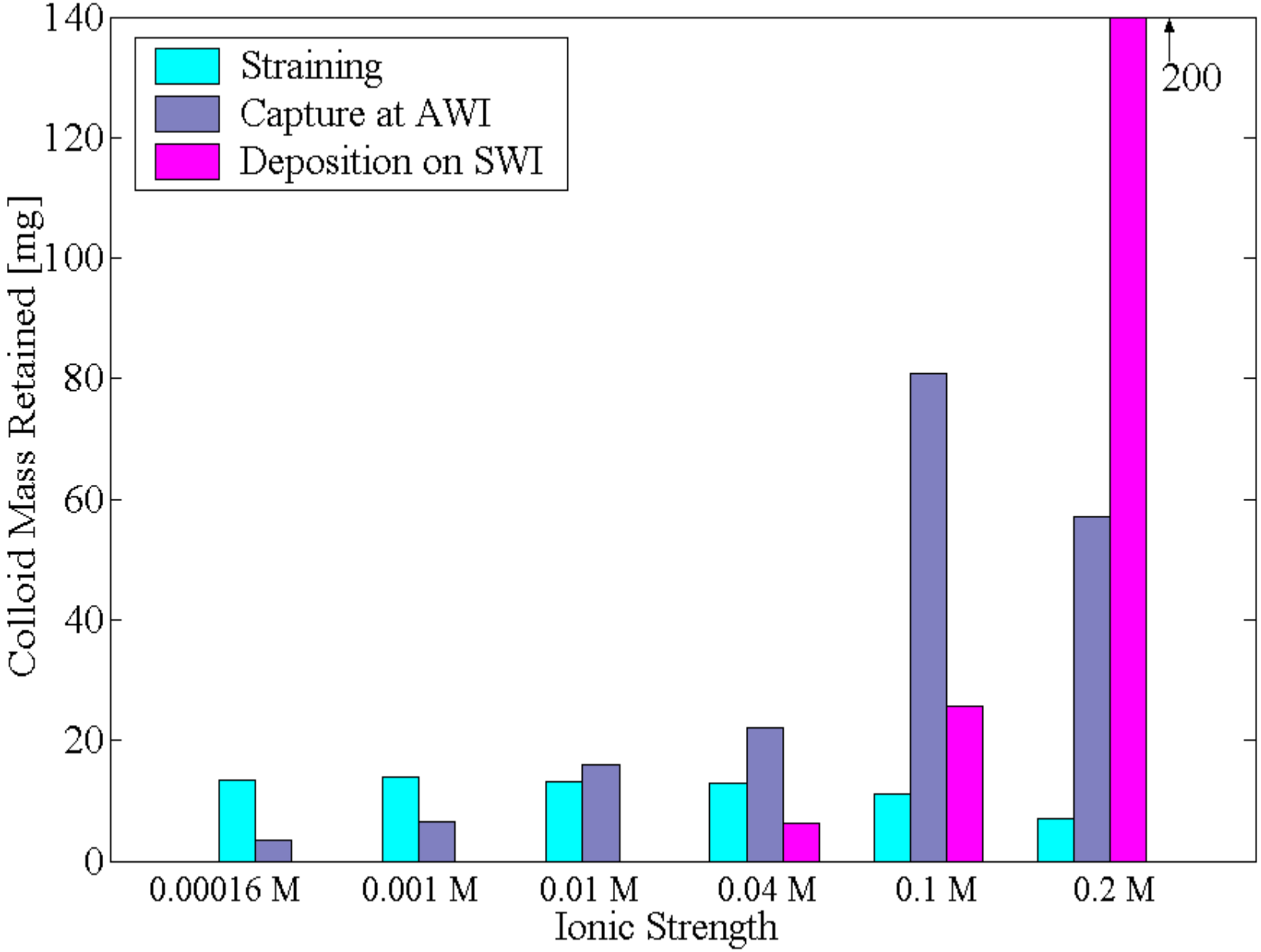


Flow-Duct Dimensions

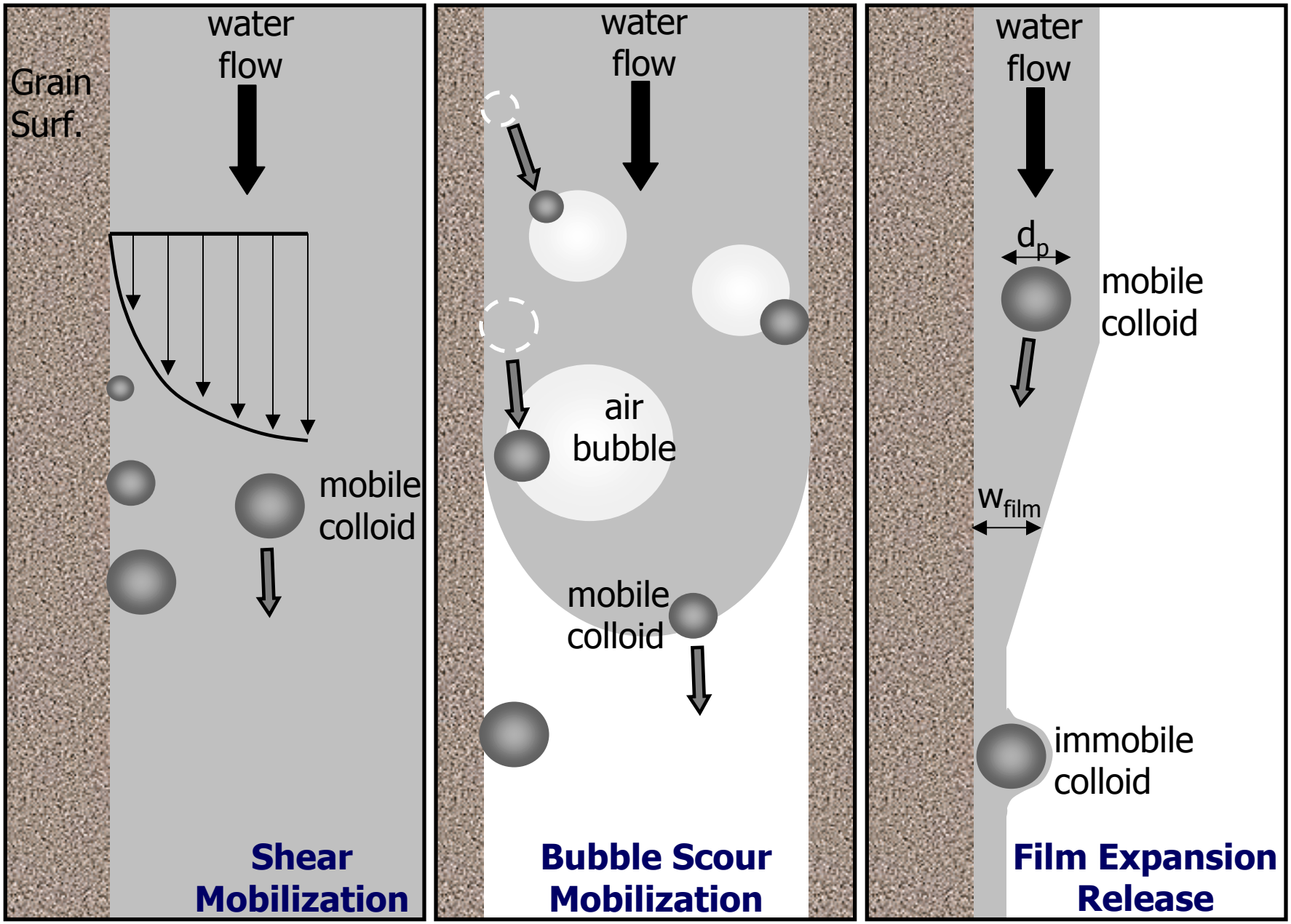


Or and Tuller, 2001

Colloid-Retention Mechanisms

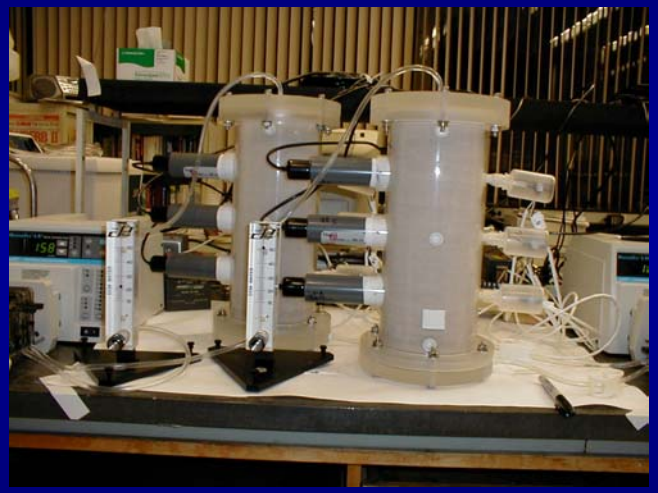


Colloid-Mobilization Mechanisms



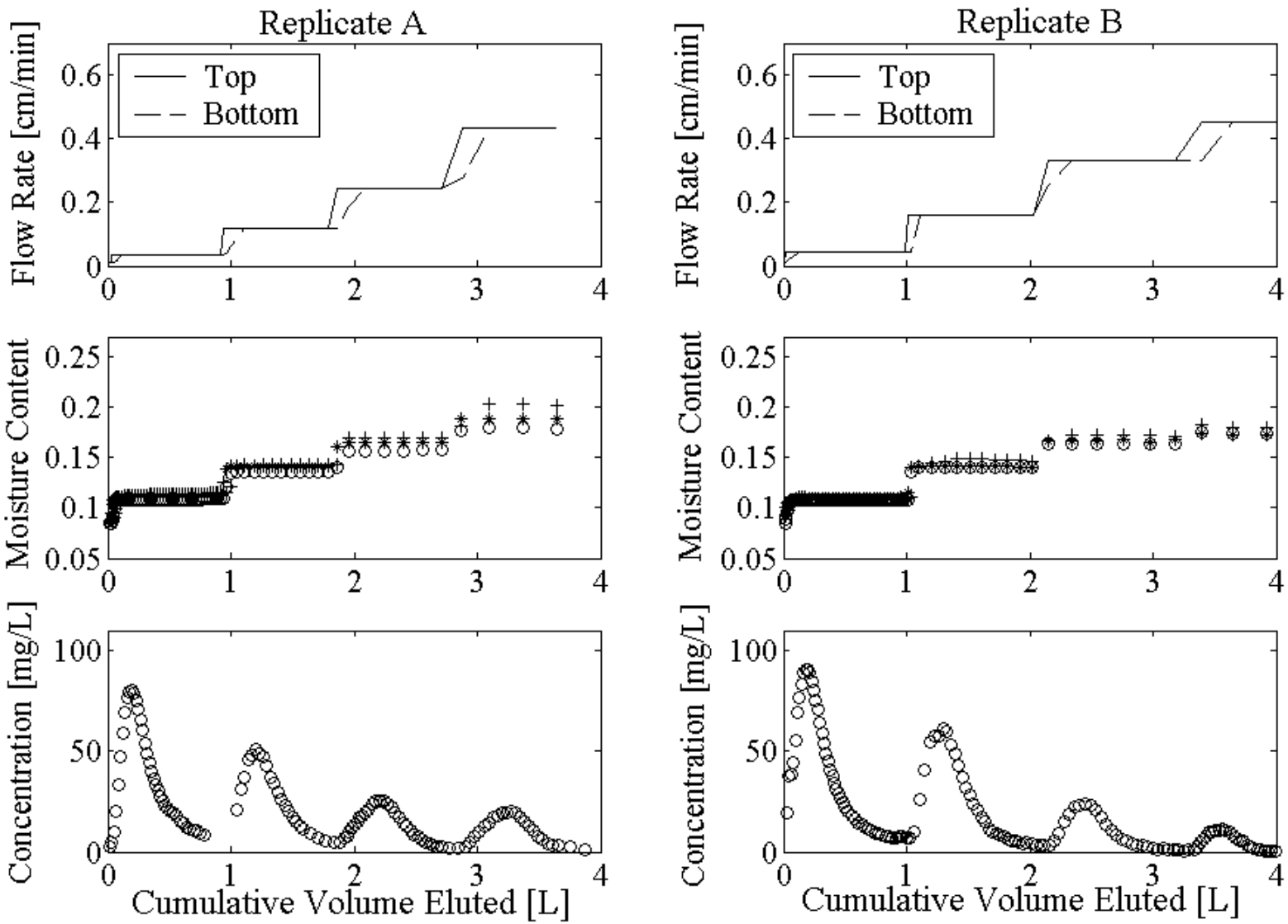
Experimental Procedure

- Stage 1: Establish steady, unsaturated flow conditions within column
- Stage 2: Introduce silica colloids without perturbing flow rates

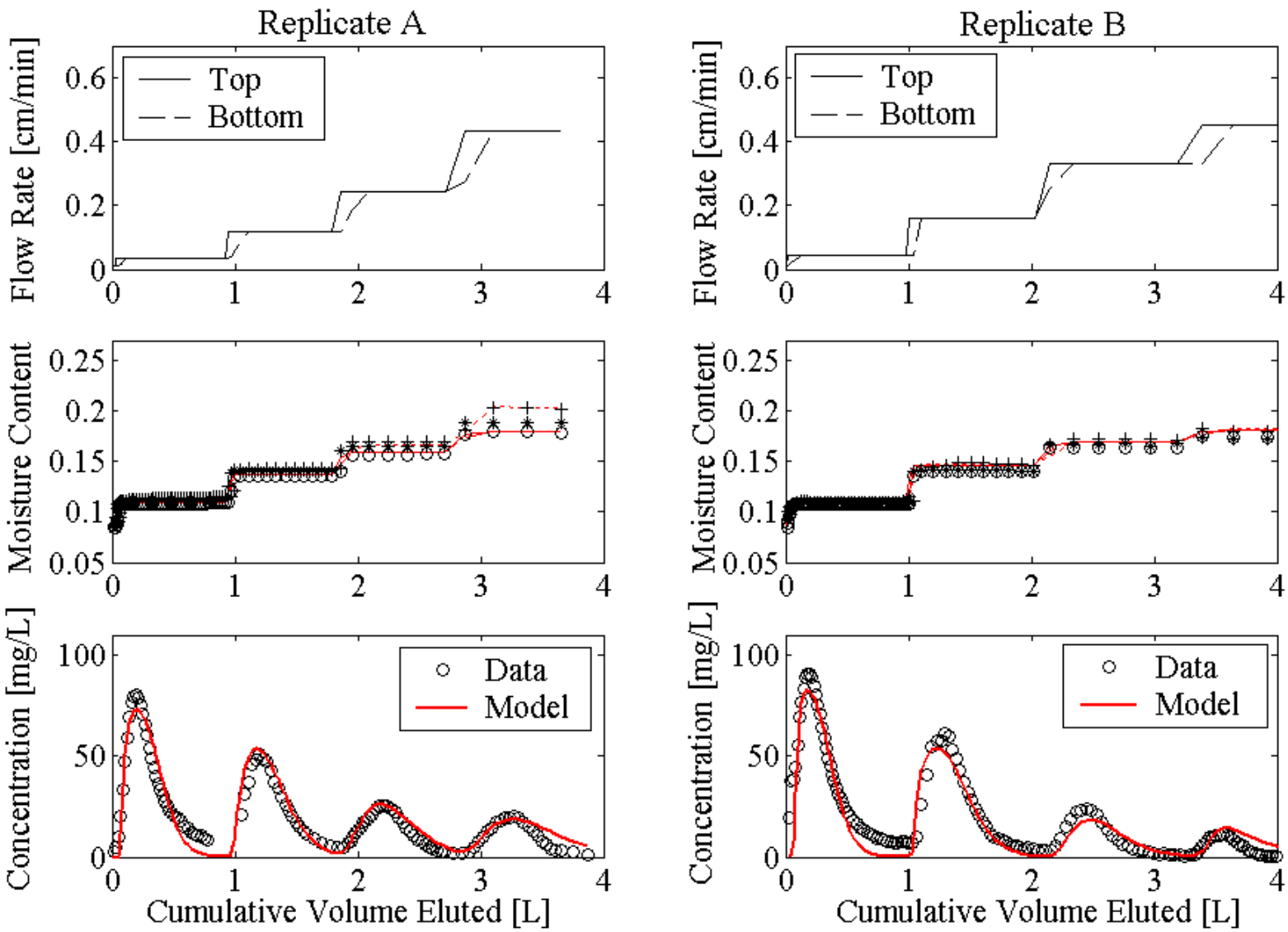


- Stage 3: Flush columns with colloid-free water
- Stage 4: Induce colloid release through step-change increases in flow rate

Experimental Results on Flow-Induced Colloid Mobilization



Comparison of Modeled and Experimental Results



Task #2: Characterizing the effects of vadose-zone heterogeneity on colloid-associated radionuclide transport

Approach

- Compare results of experiments conducted in columns of homogeneous media to those conducted in columns containing preferred flow paths

Porous media:

i) homogeneous sand
ii) "ideal" structured heterogeneities
iii) intact cores

Colloids:

i) illite clay
ii) silica-coated TiO_2 and ZrO_2

Radionuclides:

i) cesium
ii) strontium

} Colloid-radionuclide interaction kinetics measured in separate experiments

Flow regime:

i) steady unsaturated
ii) transient unsaturated

Task #3: Model Development

Approach

- **Modify facilitated-transport models for saturated media to account for complexities associated with vadose-zone environments.**

$$\frac{\partial(C_a + C_{amc}C_c)}{\partial t} + \frac{\rho}{n}\left[\frac{\partial C_{as}}{\partial t} + \frac{\partial C_{cs}C_{aic}}{\partial t}\right] = D\frac{\partial^2(C_a + C_{amc}C_c)}{\partial x^2} - v\frac{\partial(C_a + C_{amc}C_c)}{\partial x}$$

$$\frac{\rho}{n}\frac{\partial C_{cs}}{\partial t} = k_{cs}C_c - \frac{\rho}{n}k_{sc}C_{cs}$$

$$\frac{\partial C_c}{\partial t} + \frac{\rho}{n}\frac{\partial C_{cs}}{\partial t} = D\frac{\partial^2 C_c}{\partial x^2} - v\frac{\partial C_c}{\partial x}$$

$$\frac{\partial C_{amc}C_c}{\partial t} = D\frac{\partial^2 C_{amc}C_c}{\partial x^2} - v\frac{\partial C_{amc}C_c}{\partial x} + k_{ac}C_a - k_{ca}C_cC_{amc} - k_{cs}C_cC_{amc} + \frac{\rho}{n}k_{sc}C_{cs}C_{aic}$$

$$\frac{\rho}{n}\frac{\partial C_{aic}C_{cs}}{\partial t} = k_{ac}C_a - \frac{\rho}{n}k_{ca}C_{cs}C_{aic} + k_{cs}C_cC_{amc} - \frac{\rho}{n}k_{sc}C_{cs}C_{aic}$$

$$\frac{\rho}{n}\frac{\partial C_{as}}{\partial t} = k_{as}C_a - \frac{\rho}{n}k_{sa}C_{as}$$

Saiers and Hornberger, 1996

Additional Complexities

(1) Transient porewater flow

(2) Mass transfer with the air phase

(3) Porous-medium heterogeneity