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Bacteriophage Transport in Sandy Soil and Fractured Tuff

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Bacteriophage transport was investigated in laboratory column experiments using sandy soil, a controlled field study in a sandy wash, and laboratory experiments using fractured rock. In the soil columns, the phage MS-2 exhibited significant dispersion and was excluded from 35 to 40% of the void volume but did not adsorb. Dispersion in the field was similiar to that observed in the laboratory. The phage f2 was largely excluded from the porous matrix of the two fractured-rock cores studied, coming through 1.2 and 2.0 times later than predicted on the basis of fracture flow alone. Because of matrix diffusion, nonsorbing solutes were retarded by over a factor of three relative to fracture flow. The time for a solute tracer to equilibrate with the porous matrix of 6.5-cm-diameter by 25-cm-long cores was measured in days. Results of both granular-medium and fractured-rock experiments illustrate the inability of a solute tracer to provide estimates for dispersion and effective porosity that are applicable to a colloid. Bacteriophage can be used to better estimate the maximum subsurface transport rate of colloidal contaminants through a porous formation.

Colloidal particles are abundant in natural waters and are often present in larger numbers than are larger, suspended solids. Colloids are important with respect to contaminant transport in that they may facilitate the transport of sorbed species such as trace metal or organic contaminants, and they themselves may be contaminants of environmental concern. Virus and asbestos particles are two examples of the latter contaminants.

The occurrence of human enteric viruses in groundwater in locations near surface waste discharges and septic tanks has been well documented (13). Such studies indicate that viruses can travel to depths as great as 64 m and distances as great as 1,600 m under certain conditions. The study of virus particles as indicators of colloid transport in general is appealing, as they are relatively straightforward to enumerate and their chemical properties are reproducible and well known from previous work.

Two principal factors control virus fate in groundwater: their survival in the subsurface and their retention by soil particles. Moisture-holding capacity, pH, and organic matter influence both virus survival and retention. Soil particle size, cation exchange capacity, and clay content primarily influence retention. Adsorption of the viruses to the soil particle can offer protection against viral inactivation (12). Virus adsorption to soils is governed largely by electrostatic interactions and van der Waal's forces (8), with both hydrophobic and hydrophilic factors being important. Thus, for hydrophilic viruses, the isoelectric point has been shown to be an indicator of the degree of adsorption to soils and other surfaces (8). Virus isoelectric points are both type and strain dependent but are generally in the pH range of 3 to 6.

The purpose of the work described in this paper was to determine virus transport relative to that of a nonsorbing solute in subsurface porous media. Results of recent laboratory and field tracer studies in both sandy soil and fractured rock are presented.

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MATERIALS AND METHODS

Laboratory soil-column and controlled field studies were undertaken to determine the behavior of the bacteriophages MS-2 and f2 in a shallow, sandy alluvial aquifer near Tucson, Ariz. Studies of fractured rock were designed to compare the behavior of f2 to that of a solute tracer in a core sample of tuff from the Nevada Test Site, the location of previous underground nuclear weapon detonation and the proposed site for a high-level nuclear-waste repository. Coliphages MS-2 and f2 were chosen for these studies because their physicochemical structure and properties have been well characterized and because they have been shown to adsorb poorly to most soils (9; G. H. Grondin, M.S. thesis, University of Arizona, Tucson, 1987).

Virus and virus assays. Coliphages MS-2 and f2 and their bacterial hosts were obtained from the American Type Culture Collection (Rockville, Md.). Both viruses are structurally and antigenically identical (7). MS-2 and f2 were grown and purified in *Escherichia coli* B (ATCC 15597), as described by Adams (1). The PFU method of assay similar to that described by Adams (1) and Davis and Sinsheimer (6) was used. Assays were performed in trypticase soy agar (GIBCO Laboratories, Madison, Wis.). If dilutions were necessary, samples were diluted in Tris-buffered saline and adjusted to pH 7.5 (22).

Laboratory soil-column studies. An acrylic column (diameter, 5 cm; length, 1.15 m) was filled to a depth of 1.05 m with oven-dried soil from the Tanque Verde Wash field site (see below) and saturated with groundwater from the bottom to minimize air entrapment. A Mariott siphon was used to maintain a constant water level above the soil column (Fig. 1). During an experiment, flow down the column was maintained at a constant rate by fixing the outlet elevation of a 1.3-cm-diameter Tygon tube. The procedure is further described in the studies by Grondin (M.S. thesis) and Lance and Whisler (14).

Groundwater was taken from the Martin Street well on the University of Arizona campus. It had a pH of 8.1, an electrical conductivity of 378 S cm^{-1}, an alkalinity of 106 mg $liter^{-1}$, a hardness of 98 mg $liter^{-1}$, and 0.1 mg of dissolved organic matter $liter^{-1}$.

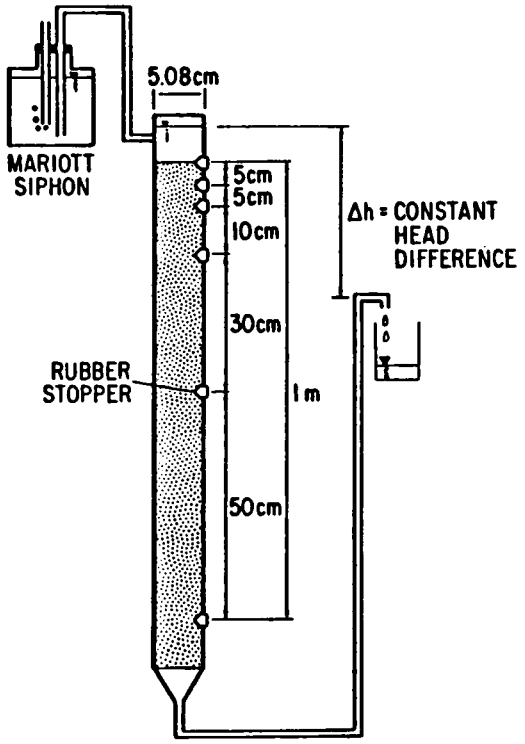

FIG. 1. Mariott siphon and column apparatus for sandy soil experiments.

TABLE 1. Fractured-rock experimental parameters

Parameter	Result for: Rock 1	Rock 2
Fracture dimensions		
Volume (cm^3)	1.04	0.39
Aperture (μm)	133	57
Effective cross-sectional area (calculated) (cm^2)	0.0865	0.0371
Tuff properties		
Sample size (cm^3)	830	830
Effective porosity[a,b]	0.24	0.24
Effective void volume (calculated) (cm^3)	200	200
Experimental variables		
Flow rate ($cm^3\ h^{-1}$)	0.66	0.34
Velocity		
cm h^{-1}	7.63	9.18
cm day^{-1}	187	225
Solute effective D ($cm^2\ s^{-1}$)[b]	4.5×10^{-7}	4.5×10^{-7}
Virus effective D ($cm^2\ s^{-1}$)	9×10^{-8}	9×10^{-8}
Fracture residence time (h)	1.57	1.15
Results		
Virus residence time (h)	1.79–1.93	2.30–2.35
Retardation factor, virus	1.18	2.02
Solute residence time (h) (50% breakthrough)	6	7–8
Retardation factor, solute	3.8	6.5

[a] Measured by mercury intrusion porosimetry.
[b] G. R. Walter, Ph.D. dissertation, University of Arizona, Tucson, 1985.

Groundwater was inoculated with MS-2 and added to the Mariott siphon, giving feed concentrations in the range 10^3 to 10^4 PFU ml^{-1}. The input concentration and column background concentrations at each sampling depth were assayed prior to each experiment. Input samples were also assayed at the end of each experiment. Samples were withdrawn with sterile, 10-ml polypropylene syringes and 20-gauge disposable hypodermic needles through column ports fitted with rubber stoppers. Samples were collected 12, 24, 48, 120, and 240 min after the flow down the column was started.

Batch studies indicated that MS-2 and f2 do not sorb to the aquifer material at 25°C (Grondin, M.S. thesis). Sorption experiments were carried out by mixing 10 and 100 g of oven-dried soil with 100-ml aliquots of groundwater containing 10^6 to 10^7 PFU of the virus ml^{-1}. Samples were assayed within 30 and 120 min.

Virus-survival experiments showed that MS-2 and f2 inactivation was not significant during the 1- to 3-day duration of our experiments. The procedure for evaluating inactivation involved making up 50 ml of a 10^5 to 10^6 PFU ml^{-1} suspension in 50-ml polypropylene centrifuge tubes and storing it at 20 to 23°C for 30 days. Assays were then done daily for 5 days and every 5 days thereafter. This procedure is described in detail by Yates et al. (22). The inactivation rate of MS-2 in Tanque Verde Wash water averaged 0.184 $\log_{10}\ day^{-1}$ and 0.101 $\log_{10}\ day^{-1}$ in Martin Street well water. The inactivation rate of f2 averaged 0.082 $\log_{10}\ day^{-1}$.

Field studies. A field site was established in a 30-m-wide section of the Tanque Verde Wash, a channel in northeast Tucson that receives periodic flows from precipitation in the Santa Catalina mountains to the north. Steel drive-point wells (diameter, 2.5 cm; length, 1.8 m) were installed along the line of flow at 0.5-ml intervals for 4.5 m. Holes (0.6 cm) were drilled in the drive-point pipes at 0.15-m intervals. A deep source box (0.6 by 0.05 by 1.2 m) was installed at the upstream end of the site. Two sides of the box consisted of metal screens to allow groundwater flow through the box. Four lateral drive-point wells were installed 0.4 and 0.8 m on either side of the last well. Elevations were determined and the groundwater flow was mapped as described by Grondin (M.S. thesis).

A field experiment involved introducing f2 and a bromide tracer into the source, periodically (6- to 20-h intervals for 2 to 3 days) taking 50-ml samples from downstream drive-point wells, and assaying for the virus. The volume of 500 to 1,000 ml was removed from each well prior to sampling. A hand-operated vacuum pump and 0.6-cm Tygon tubing were used to lift water from the 1.8-m depth for each sample. Sampling tubes were cleaned with a chlorine solution and a sodium thiosulfate solution before each use.

Fractured-rock experiments. Groundwater containing 10^5 PFU of the phage f2 ml^{-1} and 4.0 mg each of thiocyanate and pentafluorobenzoic acid (PFB) $liter^{-1}$ was pumped through two core samples of tuff (diameter, 6.5 cm; length, 25 cm) from a saturated formation at the Nevada Test Site; each sample contained a single longitudinal fracture. The cores were sealed at the edges with epoxy and fitted with Teflon microbore tubing at the ends. The cores and their physical dimensions (Table 1) were provided by the Los Alamos National Laboratory (New Mexico). Groundwater from the site (pH 7.6; total dissolved solids, 400 mg $liter^{-1}$) was used to make up feed solutions; both cores were immersed in formation water before and during each experiment. Temperatures were 19 to 23°C. Two 24-h experiments were run on each core, with conditions as noted in Table 1. Fractions containing 0.01 ml of eluate were periodically collected and mixed with 0.05 ml of Tris buffer before analysis.

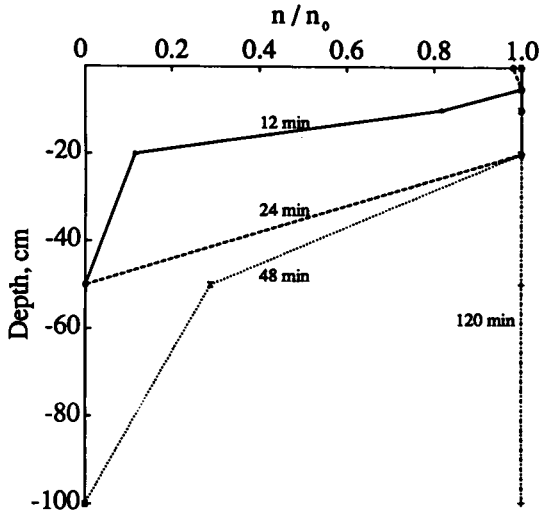

FIG. 2. Virus concentration versus depth at four times for soil-column experiment 2, MS-2 in tap water; u = 0.47 cm min^{-1}; n_0 = 8×10^3 PFU ml^{-1}; temperature, 25°C. Breakthrough in the 100-cm column occurred by the time of the 120-min sample.

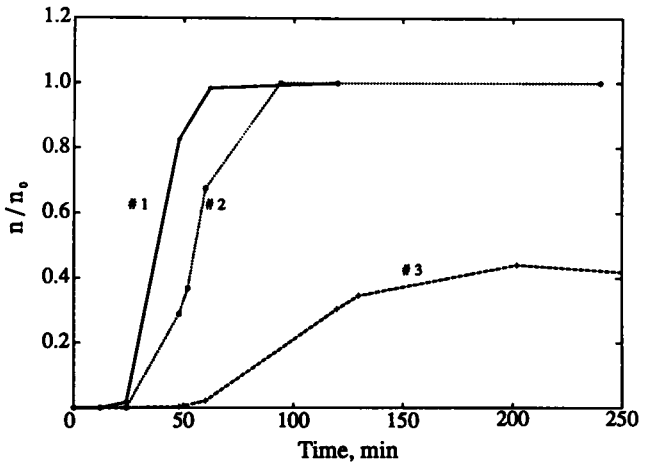

FIG. 3. Breakthrough curves (50-cm depth) for soil-column experiments 1 to 3, MS-2 in tap water; experiment 1 had the highest velocity (Table 2) and earliest breakthrough. n_0 was 6×10^3, 8×10^3, and 14×10^3 PFU ml^{-1} for the three experiments; the temperature was 25°C. The lower values for experiment 3 reflect die-off (0.001 $\log_{10}$ min^{-1}) in the feed water.

Dissolved-species concentrations were determined by high-performance liquid chromatography using a Spectra Physics SP8700 liquid chromatograph with a 7125 injection valve (200-μl loop; Rheodyne, Inc., Cotati, Calif.) and a Hitachi model 10-40 variable-wavelength UV detector. The column was 25 cm in length and had a 4.6-mm inside diameter and was packed with 10-μm strong anion exchange media (Whatman, Inc., Clifton, N.J.). The mobile phase was a phosphate solution, made from potassium permanganate-distilled water.

A batch f2 phage survival experiment in the formation water showed no decrease in concentration (4.1×10^8 PFU ml^{-1}) within 48 h, so die-off was taken as insignificant in the transport experiments. Sorption of phage was also assumed to be negligible; a mixture of 14 g of ground tuff (−270 mesh) and 30 cm^3 of formation water containing 10^6 PFU ml^{-1} showed no decrease in virus concentration over 30 min. This study (Grondin, M.S. thesis) and previous studies (9) have shown that 30 min is adequate for adsorption to occur.

RESULTS

Laboratory soil-column studies. The batch results suggested that the virus would move through the soil columns as a conservative species (no sorption or die-off). Virus breakthroughs at the various depths in the column experiments (Fig. 2) were slightly ahead of the water displacement, suggesting volume exclusion and some dispersion of the 23-nm virus particles. The breakthrough curves on Fig. 3 also show significant dispersion. The third experiment exhibited significant die-off, estimated to be on the order of 0.001 min^{-1} for n_0. Results for three experiments (Table 2) indicated that dispersion increases with velocity, as expected, and that 35 to 40% of the pore volume is inaccessible to the virus. Dispersion coefficients were determined from the standard deviation on a probability plot of the virus concentrations in the column at a given time versus depth (16). The pore volume from which virus particles are excluded is equal to 1 minus the ratio of the time for virus breakthrough (at $n/n_0 = 0.5$) to the hydraulic detention time in the column. This is equal to 1 minus the conventional retardation factor, R, used in transport models.

Field studies. Comparison of the phage (Fig. 4) and bromide tracer results indicated that dispersion in the field is similar to that measured in the laboratory; i.e., there is some longitudinal spreading. Although qualitatively there was some volume exclusion, no estimate could be made of the amount because of uncertainties in interpreting differences in the bromide and f2 experiments. Groundwater velocities for the two experiments were not computed, as hydraulic conductivity could not be measured in the field. Phage concentrations in the lateral drive-point wells were generally below an n/n_m value of 0.005, indicating only a small amount of plume spreading. n_m is the maximum virus concentration observed in samples from the wells.

Fractured-rock experiments. Breakthrough curves (Fig. 5) showed the phage coming through before a conservative tracer, with little dispersion. Results for experiments 1 and 2 were essentially the same for each rock sample. The dissolved tracers came through later and did not reach the inlet concentration in 24 h. As the breakthrough curves for the chemically different thiocyanate and PFB were essentially the same, matrix diffusion rather than sorption was apparently responsible for their retardation. The phage was largely excluded from the porous matrix of the tuff and thus came through much sooner.

The phage were retarded relative to the calculated residence time in the fracture alone, but they exhibited very little dispersion. The lack of dispersion suggested that the phage were not diffusing into the porous matrix of the tuff. However, this observation is in contrast to the estimate that more than two-thirds of the total porosity in the tuffs from the Nevada Test Site is in pores greater than 0.1 μm in

TABLE 2. Dispersion and retardation parameters for soil-column experiments

Expt no.	Velocity (cm min^{-1})	R	Dispersion (cm^2 min^{-1})
1	0.81	0.54	1.04
2	0.47	0.61	0.92
3	0.38	0.61	0.84

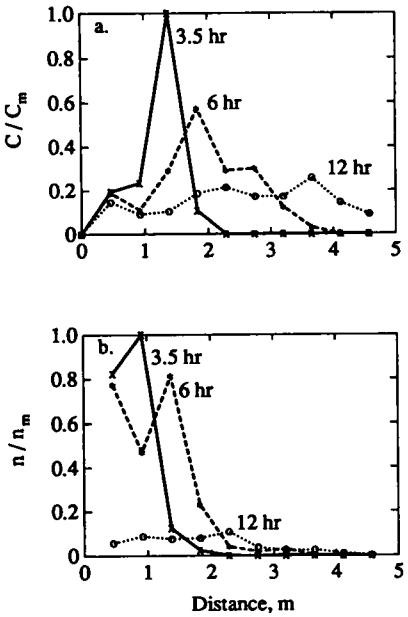

FIG. 4. Concentration versus distance results of (a) bromide and (b) f2 phage transport in the field; n_{max} = 4.9 × 10^5 PFU ml^{-1}; temperature, 21°C; hydraulic gradient, 0.007. The diminishing of the peak n/n_{max} with distance and spreading of the concentration profiles was due to dispersion. Retardation results in the bromide and f2 are not directly comparable because of different velocities.

diameter (21). The phage are only approximately 0.023 μm in size. Either phage adsorption or diffusion into large but possibly shallow pores of the matrix could be responsible for the apparent retardation. Although the batch experiment failed to demonstrate adsorption, a higher effective solid-to-liquid ratio in the core would result in sorption being observed only in the core.

Whereas the phage were retarded by factors of 1.2 and 2.0 in rocks 1 and 2 (relative to fracture flow), respectively, the solutes were retarded by factors of 3.8 and 6.5, respectively. Note that the solute was retarded more relative to fracture flow in rock 2, but the ratio of solute and virus residence times is the same in both rocks. Rock 2, which has the smaller aperture, showed both more retardation and a lower concentration of the dissolved species than rock 1 (Fig. 5), consistent with the findings of Grisak and Pickens (10) that decreasing the aperture size results in more solute storage in the rock matrix.

DISCUSSION

Two approaches to interpreting results of the fractured-rock experiments in terms of the mathematics of solute advection, dispersion, and retardation were applied: (i) an explicit, microscopic description of solute advection in the fracture, together with diffusion into the porous matrix (11); and (ii) an empirical model describing solute exchange between mobile and immobile regions (3, 20). The relation between parameters in the two types of models has been explicity described (19).

In the matrix diffusion model, the solute concentration (C_c) in the fracture (or n_c for virus) is controlled by advection in the fracture and diffusion into the matrix:

$$b\left[\frac{\partial C_c}{\partial t} + \left(u\,\frac{\partial C_c}{\partial z}\right)\right] = \theta_i D^* \frac{\partial^2 C_i}{\partial y^2} \qquad (1)$$

where b is the fracture half-aperture width, u is the water velocity in the fracture, θ_i is the matrix porosity, and D^* is the effective molecular diffusion coefficient of the solute (or virus) in the matrix. C_i is the solute (n_i for virus) concentration in the matrix, given by

$$\frac{\partial C_i}{\partial t} = D^* \frac{\partial^2 C_i}{\partial y^2} \qquad (2)$$

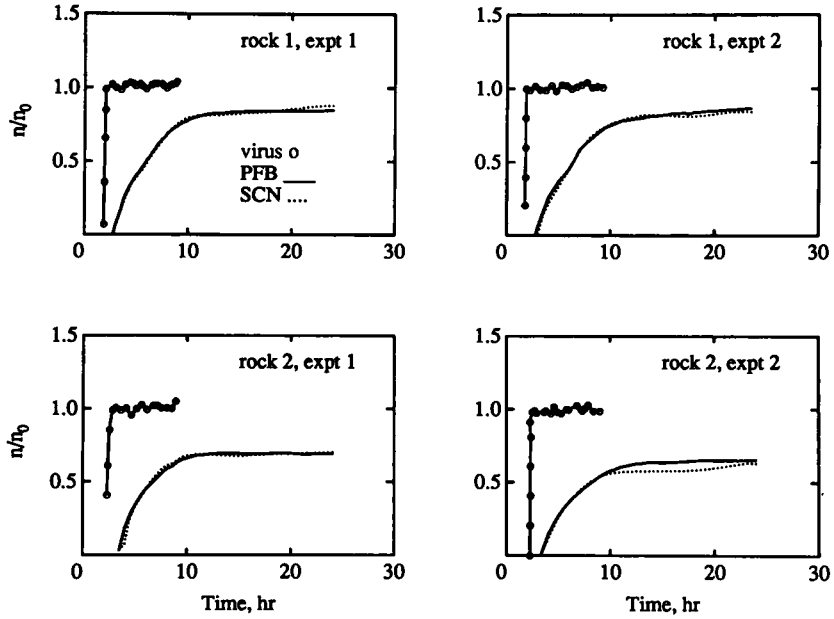

FIG. 5. Breakthrough curves for f2 phage and dissolved tracer transport in fractured-rock experiments; n_0 = 10^5 PFU of phage ml^{-1} and C_0 = 40 mg of dissolved species $liter^{-1}$. Phage broke through with no dispersion and only a small amount of matrix diffusion because of their size relative to that of pores in the matrix. Dissolved tracers exhibited dispersion and failed to reach C/C_0 of 1.0 because of matrix diffusion. SCN, Thiocyanate.

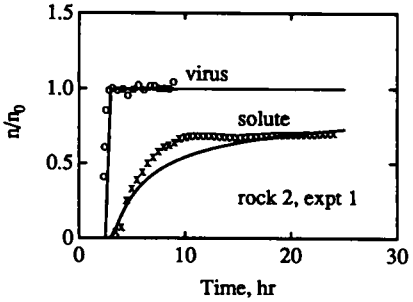

FIG. 6. Best visual fit of matrix diffusion model to virus and solute breakthrough curves; $D = 1.2 \times 10^{-7}$; other parameter values are as noted in Table 1. Model failed to fit both breakthrough curves with the same set of parameters.

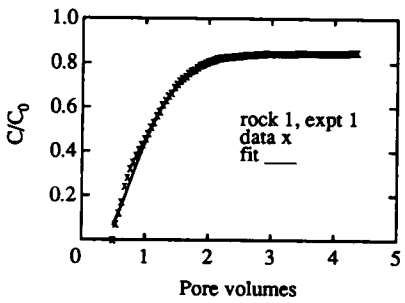

FIG. 7. Fit of first-order model to solute breakthrough curve for $L/u = 5.5$. Several parameter choices will fit solute data (e.g., Table 3); virus data could not be fit.

The solution for these equations for the appropriate boundary conditions is given by Grisak and Pickens (11).

The matrix diffusion model did not provide a good fit to the solute breakthrough curves of Fig. 5, but it did fit the virus breakthrough curves. Because independent estimates were available for average values of the key parameters (aperture width, flow velocity, effective porosity, and matrix diffusion coefficient), they were constrained to ±50% of the values given in Table 1. The fitted curves failed to model the steep rise followed by the slowly increasing curve segment (e.g., Fig. 6).

Governing equations for one-dimensional solute transport in a porous medium containing both mobile and immobile regions, with slow transfer between the regions and with sorption in both regions, have been given by various investigators (5, 15, 19, 20):

$$[\theta_e + f\phi K_p]\frac{\partial C_e}{\partial t} + [\theta_i + (1-f)\phi K_p]\frac{\partial C_i}{\partial t} = \theta_e D\frac{\partial^2 C_e}{\partial z^2} - u\theta_e\frac{\partial C_e}{\partial z} \quad (3)$$

$$[\theta_i + (1-f)\phi K_p]\frac{\partial C_i}{\partial t} = \alpha_f (C_e - C_i) \quad (4)$$

$$S_e = K_p C_e \quad (5)$$

$$S_i = K_p C_i \quad (6)$$

where C_e and C_i are the solute concentrations in the mobile and immobile regions, respectively (n_e and n_i for virus); S_e and S_i are the respective bound concentrations; θ_e and θ_i are the porosities in mobile and immobile regions, respectively; ϕ is the dry bulk density of the solid material; f is the fraction of sorbent in the mobile region; D is the longitudinal dispersion coefficient; u is the average interstitial velocity, as described above; and α_f is a mass-transfer coefficient (s^{-1}), which depends on the solute's molecular diffusion coefficient and the geometry of the immobile region (e.g., diffusion distance, size and shape of pores, etc.) (4). Equation 3 expresses the total change in concentration with time due to advection and dispersion. In equation 4, the change in immobile-phase concentration with time is the product of the mass-transfer coefficient and the difference in mobile- versus immobile-phase concentration. Equations 5 and 6 express the linear adsorption equilibria; any adsorption to the rock or penetration into the matrix is thus assumed to be reversible. For no adsorption, $K_p = 0$.

The mobile-immobile transport model of equations 3 to 6 (four parameters) did provide a good fit to the solute data (Fig. 7). A three-parameter ($f = 0$) model (first-order model) could also be fit to the data. Parameter values were optimized by using the curvefitting routine of VanGenuchten (18). Breakthrough curves were normalized to various choices of the residence time for a conservative tracer (i.e., pore volume), and results were calculated (Table 3). The most important parameters were the (dimensionless) first-order rate coefficient (ω), which is equivalent to a Damkohler number (2, 17), and the Peclet number (P). ω is given by

$$\omega = \frac{\text{physical time scale}}{\text{chemical time scale}} = \frac{L/u}{\theta_e/\alpha_f} \quad (7)$$

where L is the length of the fracture. When ω is greater than 100, local equilibrium applies; and as ω drops below about 0.1 to 0.5, sorption is too slow to observe and the solute appears to be conservative. The Peclet number is given by

$$P = \frac{Lu}{D} \quad (8)$$

and indicates the time scale for dispersion divided by the residence time in the system.

The fit was much less sensitive to the retardation factor (R) and the fraction mobile versus immobile liquid parameter (β) (two-site model only); both had standard errors exceeding the parameter estimate in all cases. R and β are defined by

TABLE 3. Model fit to thiocyanate breakthrough curves for rock 1, experiment 1

Model and L/u	P		ω		SSQ[a]
	Value	SE	Value	SE	
First-order model (three parameters)					
1.0	0.20				0.8382
5.0	9.14		0.227		0.0301
5.5	7.40	0.38	0.141	0.008	0.0209
6.0	6.90	0.82	0.117	0.021	0.1272
Mobile-immobile model (four parameters)					
1.0	7.57	0.37	0.153	0.010	0.0142
2.0	7.58	0.37	0.154	0.010	0.0142
6.0	7.58	0.37	0.154	0.010	0.0141
10.0	7.54	0.37	0.152	0.010	0.0141

[a] Sum of square errors.

$$R = 1 + \frac{\phi K_p}{\theta_e + \theta_i} \quad (9)$$

$$\beta = \frac{\theta_e + f\phi K_p}{\theta_e + \theta_i + \phi K_p} \quad (10)$$

Interpretation of parameters from these models is not straightforward, however, as the mathematical descriptions do not correspond to the physical situation as well as with the matrix-diffusion model.

For rock 1, the first-order model would only give a good fit with L/u, the residence time for a conservative tracer, in the range of 5 to 6 h. Note that this corresponds well to the observed $C/C_0 = 0.5$ breakthrough of the thiocyanate and PFB (Fig. 5). The mobile-immobile model could be fit with a much wider choice of L/u values, and the fitted Peclet number and mass-transfer coefficient were relatively insensitive to the choice. Taking an average P of 7.6, with L/u = 5.5 h and L = 25 cm, gives $u = 1.26 \times 10^{-3}$ cm s^{-1} and $D = 4.15 \times 10^{-3}$ cm^2 s^{-1}. The magnitude of D reflects matrix diffusion as the main process contributing to dispersion.

Interpretation of ω in terms of a first-order rate coefficient for detachment (or release from the matrix) depends on the value of the retardation factor, which had a large standard error in the fits (Table 3). For reversible adsorption, the forward (α_f) divided by reverse (α_b) rate coefficient equals the dimensionless partition coefficient ($R = 1$). ω is related to α_b by $\alpha_b = \omega u/[(R - 1)L]$. For PFB in rock 1, experiment 1, $\omega = 0.156$, $u = 2.12 \times 10^{-3}$ cm s^{-1}, L = 25 cm, and R = 10, giving $\alpha = 1.45 \times 10^{-6}$ s^{-1}. Since the solute does not adsorb to the solid material, $R - 1$ is not a dimensionless equilibrium partition coefficient; it can be viewed as the ratio of the forward and reverse rate coefficients or mass-transfer coefficients. Taking this ratio to be one, which is well within the standard error of estimating R, gives α_b about one order of magnitude lower. The time scale for a solute to equilibrate with the rock matrix is thus on the order of 1 to a few days. The observed ω's in the range of 0.15 are near that lower limit of those observable; smaller values result in the solute behaving like a conservative tracer.

Interpretation of the mobile-immobile model parameters requires a value for θ_e/θ, or the fraction of the porosity in the mobile region, in addition to those parameters noted above. Over 99% of the sample porosity was in the porous matrix, but this is not a physically meaningful parameter in the present case because of different system geometries.

Conclusions. The experiments in sandy aquifer material support prior observations (13) that virus particles can persist and travel several meters in sandy aquifers. Virus concentrations along the flow show evidence of dispersion but not retardation. The apparent exclusion from 35 to 40% of the pore volume in the granular-medium experiments suggests that virus should travel 1.6 to 1.9 times faster than a conservative tracer, however.

In the studies reported here, the virus and solutes do not adsorb. In interpreting results of adsorbing biocolloids in either granular or fractured media, the dispersion and retardation behavior must first be characterized from observations of a "conservative" colloid. The results illustrate the inability of a solute tracer to provide estimates for dispersion and effective porosity that are applicable to a colloid such as a virus.

Comparison of the bacteriophage and dissolved-species breakthrough curves in the fractured-rock experiments indicates that tracers subject to the effects of matrix diffusion will not provide actual groundwater velocities from field tracing tests. Bacteriophage can be used to better estimate the maximum subsurface transport rate of colloidal contaminants through a porous formation. MS-2 and f2 act conservatively with respect to sorption in the media studied. Therefore, coliphage and potentially pathogenic human enteric viruses could travel faster than chemical contaminants originating from the same source. Attempts to estimate safe distances between waste sources and domestic groundwater supplies should take this factor into consideration.

Since retardation is related to the surface properties of the virus, different viruses should travel at different rates through the porous media used in this study. Poliovirus type 1 (LSc), for example, which readily adsorbs to soils (9), could be expected to be retarded more than the MS-2 and f2 coliphages. Thus, these coliphages could be seen as a worst-case model for virus movement.

ACKNOWLEDGMENTS

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