Title: Sorption Behavior of Strontium-85 onto Colloids of Silica and Smectite

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ABSTRACT

Strontium-90 is one of the sizable radioactive contaminants found in DP Canyon at Los Alamos, New Mexico. Radioactive surveys found that $^{90}\text{Sr}$ is present in surface and groundwater in DP Canyon and Los Alamos Canyon. Colloids may influence the transport of this radionuclide in surface water and groundwater environments in both canyons. In this study, we investigated the sorption/desorption behavior of Sr on colloids of smectite and silica. Laboratory batch sorption experiments were conducted using $^{85}\text{Sr}$ as a surrogate to $^{90}\text{Sr}$. Groundwater, collected from DP Canyon and from Well J-13 at Yucca Mountain, Nevada, and deionized water were used in this study. Our results show that 92% to 100% of $^{85}\text{Sr}$ was rapidly adsorbed onto smectite colloids in all three waters. Adsorption of $^{85}\text{Sr}$ onto silica colloids varied within the three waters. The concentrations of Ca$^{2+}$ significantly influence the adsorption of $^{85}\text{Sr}$ onto silica colloids. Desorption of $^{85}\text{Sr}$ from smectite colloids is much slower than the sorption process. Desorption of $^{85}\text{Sr}$ from silica colloids was rapid in DP groundwater and slow using J-13 groundwater and deionized water.

INTRODUCTION

Strontium-90 is the third most frequently occurring radionuclide in groundwater at Department of Energy (DOE) facilities (1). At Los Alamos, New Mexico DP Canyon was subject to radioactive contaminant releases between 1945 and 1978 from the Plutonium Processing Facility. These resulted in the soils/sediments containing multiple radioactive contaminants. The radiological survey in 1992 and 1993 identified that a plume of radionuclides including $^{137}\text{Cs}$, $^{241}\text{Am}$, $^{239}\text{Pu}$ and $^{90}\text{Sr}$ are stored in the sediments of DP Canyon. Strontium-90 is one of the sizable contaminants in DP Canyon. Recent survey show that the radioactivity of $^{90}\text{Sr}$ in the sediments of DP Canyon ranges from 277.5 to 1231.6 Bq kg$^{-1}$, which is 1.5 to 8 times as much as its regulatory action level, called the soil Screening Action Level (SAL), require by LANL (2).
Strontium-90 desorbs from soil/sediments continuously for a long time and it has a fast migration rate relative to other contaminants including $^{137}$Cs, $^{239}$Pu, and $^{241}$Am. Average vertical migration rates of $^{90}$Sr in an saturated soil layer were estimated to be 4.2 mm yr$^{-1}$ when an average rate of soil water movement was 2500 mm yr$^{-1}$ during the forty years after the explosion of the atomic bomb at Nagasaki, Japan in 1945 (3). Radiological survey in 1995 found that as much as 526 pCi L$^{-1}$ of $^{90}$Sr exist in shallow alluvial wells of DP Canyon. This is far in excess of the drinking water standard (8 pCi L$^{-1}$). The $^{90}$Sr in surface water has been flowing through DP Canyon, and contaminates the major surface water pathways in Los Alamos Canyon.

Colloids are any organic and inorganic particles with sizes ranging from about 1 to 2 nm for organic macromolecules up to 1 μm for fragments of clays, oxides, and other solids in groundwater. It was found that colloids of clays, silica, and iron oxides were formed in the groundwater and the stability of clay and silica colloids is correlated to the ionic strength of groundwater (4). These colloidal particles have similar composition and surface characteristics to the immobile aquifer solids but are mobile within aquifers. Colloids are capable of associating with radionuclides (5, 6). The large surface area of colloids ($10^4$ to $5 \times 10^5$ m$^2$ kg$^{-1}$) can significantly sorb radionuclides even for relatively low mass concentrations of colloidal particles in the aquifer (7). In porous media, the size of colloids is smaller than the pores, which allows colloids to migrate over long distances. Therefore, these mobile colloids may enhance the transport of the strongly sorbing radionuclides along flowpaths. We found that colloids of hematite, goethite, smectite, and silica rapidly sorbed soluble Pu(V) as well as colloidal Pu(IV) in groundwater (8, 9). While sorption of Pu(V) was slow, sorption of colloidal Pu(IV) was rapid. We also found that the sorption of Pu by hematite, goethite, smectite, and silica was much faster than the desorption process. However, the role of colloids in the $^{90}$Sr transport in surface water and groundwater is not well understood. Colloids and fine sediment particles may influence transport of this radionuclide in surface water during storm events that transport sediments along the water course. This surface water recharges shallow alluvial groundwater in both DP and LA canyons. This information is important for the implementation of existing remediation technologies to control $^{90}$Sr transport. We performed laboratory batch sorption experiments using $^{85}$Sr as a surrogate to $^{90}$Sr to evaluate: 1) sorption of $^{85}$Sr onto silica and smectite colloids as affected by water chemistry, 2) sorption kinetics of $^{85}$Sr onto silica and smectite colloids, and 3) desorption of $^{85}$Sr from $^{85}$Sr-loaded colloids as a function of time. DP Canyon groundwater, Well J-13 water, and deionized water were used as media in this study.
EXPERIMENTAL PROCEDURE

Solutions

The solutions used in this study were Well J-13 water (J-13), DP Canyon groundwater (DP), and nanopure deionized water (DI). Well J-13 water was collected in the fall of 1994 from the Well J-13 at Fortymile Wash, east of Yucca Mountain, Nevada and referred to as J-13 water. DP Canyon groundwater was collected in January, 1998 from Well LAUZ-1, DP Canyon, Los Alamos, New Mexico. The waters were filtered through a 0.05 μm nylon filter membrane to eliminate natural colloids existing in the water. The composition of the filtered water was analyzed using an inductively coupled plasma spectrometry (ICP). The pH of the water was measured as well. The pH of nanopure deionized water was adjusted to 8.0 using 0.01 N of NaOH solution.

Preparation of Colloidal Solutions

Smectite Colloidal Solutions

Smectite mineral powder (particle size of < 1.0 μm), provided by University of Missouri, Columbia, Source Clay Mineral Repository, was used in this study. The cation exchange capacity (CEC) of smectite was determined using a method described by Sumner and Miller (10). The colloidal solutions, including smectite-J-13, smectite-DP, and smectite-DI, were prepared by dispersing a certain amount of smectite in a given amount of water using a sonifier/cell disrupter for 10 minutes. The dispersed suspension was allowed to stand for 5 hours at room temperature. Thereafter, the supernatant solution was carefully collected and used as a colloidal solution. The pH of the colloidal solution was measured. The mass of the colloidal particles in the solution was determined by the difference in the weights before and after vaporizing (air-drying) and oven-drying (105°C) a given amount of each solution. The particle size distribution of colloids in the solution was measured using a high sensitivity liquid in-situ spectroscopy (HSLS) from Particle Measuring Systems Inc. The surface area of smectite colloidal particles was measured using the sorption procedure of ethylene glycol monoethyl ether (EGME) described by Carter (11).

Colloidal Silica Solutions

Synthetic colloidal silica solution of SNOWTEX-ZL (ST-ZL), from Nissan Chemical Industries Ltd., was used. The solution was manufactured by dispersing negatively charged amorphous silica particles in water. To clean the colloidal silica from surfactants (e.g., Na⁺ and K⁺), the following dialysis procedure was used. Approximately 50 ml of manufactured silica
solution was diluted to 200 ml with nanopure water. The diluted colloidal solution was transferred to a 12,000-14,000 molecular weight cut-off membrane, referred to as dialysis tubing. The tubing was sealed and placed in a container with nanopure water. The surfactants of silica colloidal solution were washed by a diffusing-dialysis process. During the 50 days, the water in container was changed with fresh nanopure water at various periods of time. At the same time, 10 ml of cleaning colloidal silica solution were collected and filtered through a 0.05 μm membrane by air-pressure method. The concentrations of Na, K, Ca, Mg, Si, and Al in the filtered solution were analyzed by ICP. The pH of colloidal solution and filtered solution was measured. After the colloidal solution was cleaned, the pH of the cleaned silica colloidal suspensions was adjusted to 8.4 by adding solid NaHCO\textsubscript{3} and Na\textsubscript{2}CO\textsubscript{3}. Then the silica colloidal suspension was stored in a refrigerator for later use. The mass of the colloidal particles in the cleaned solution was determined.

**Strontium-85 tracer solution**

The \(^{85}\text{Sr}\) stock solution contained 1.0 mCi of Sr in 0.1 M HCl, and consists of 99.98% of \(^{85}\text{Sr}\) (half life \(t_{1/2} = 64.8\) d). The \(^{85}\text{Sr}\) activity of 1.0 mCi was measured in January 14, 1998 when \(^{85}\text{Sr}\) stock was shipped to the Lab. A \(^{85}\text{Sr}\) work solution was prepared by diluted 0.15 g of \(^{85}\text{Sr}\) stock solution with 999.85 g of nanopure deionized water. The activity of the work solution was determined using a gamma spectroscopy. The result was corrected by a fact of 0.28 (the efficiency of the gamma spectroscopy) and also by decay factor related to January 14, 1998, referred to as \(t = 0\). The \(\gamma\) activity of the \(^{85}\text{Sr}\) work solution was 632,555 counts per minute per milliliter (CPM ml\(^{-1}\)). The pH value of the work solution is 5.91.

**Sorption Procedure**

Three sorption experiments, referred to as Sorption #1, Sorption #2, and Sorption #3 were performed in duplicate at room temperature. In Sorption #1, approximately 0.5 g of smectite or silica colloids was transferred to an Oak Ridge centrifuge tube (50-ml). A 20 ml portion of each water (e.g., J-13, DP, or DI water) and 3 ml of \(^{85}\text{Sr}\) work solution were added to the colloids and agitated on an orbital shaker at 150 rpm for 7 days. At the same time, blank samples were also set up using 20 ml of smectite-free or silica-free DP, J-13 or DI water and 3 ml of \(^{85}\text{Sr}\) work solution.
At the end of the sorption process, the samples and blanks were centrifuged at 38,300 g for 1 hour. The supernatant of smectite colloids was filtered successively through a 0.45-μm and a 0.1-μm nylon syringe filter. The supernatant of silica colloids was filtered through a 0.05-μm nylon filter membranes by vacuum method. The pH of the filtered solution was measured. The γ activities of the filtered solution were measured as follows: one milliliter of each sample was placed into a counting tube and counted for 20 minutes by gamma spectroscopy. The results were then converted to counts per minute per milliliter (CPM ml⁻¹) and corrected by a factor of 0.28 (the efficiency of the gamma spectroscopy), followed by decay correction related to the initial time, January 14, 1998, referred to as t = 0. The adsorbed values of $^{85}$Sr onto colloids of smectite or silica were corrected with results from blank samples.

The experiment of Sorption #2 was performed to examine the sorption kinetics of $^{85}$Sr on smectite and silica colloids. In Sorption #2, 0.5 g of smectite or silica colloids, 20 ml of each water (e.g., DP, J-13, or DI water) and 3 ml of $^{85}$Sr work solution were placed into an Oak Ridge centrifuge tube (50-ml). The mixture was agitated on an orbital shaker at 150 rpm. The contact periods for colloids with $^{85}$Sr were 1, 4, 24, 48, and 96 hours. At the same time, blank samples were also set up using 20 ml portions of smectite-free or silica-free J-13, DP or DI water and 3 ml of $^{85}$Sr work solution. At the end of each contact period, the solutions were separated by applying the same centrifuge, filter and γ activity counting procedures used in Sorption #1. The results were corrected by 0.28, decay factor and results from blank samples. Centrifugation and filtration did not effect the γ activity of $^{85}$Sr in blank samples.

The experiment of Sorption #3 was conducted to examine the effect of Ca concentration on the sorption of $^{85}$Sr on silica colloids. In Sorption #3, the diluted DP waters of 0% DP+100% DI, 25% DP+75% DI, 50% DP+50% DI, 75% DP+25% DI, 100% DP+0% DI, and 100% nanopure water, were used. Half gram of silica colloids, 20 ml of each water and 3 ml of $^{85}$Sr work solution were placed into an Oak Ridge centrifuge tube (50-ml) and agitated on an orbital shaker at 150 rpm for 7 days. The same centrifuge and filter and γ counting procedures used in the sorption # 1 were applied. At the same time, blank samples were also set up using 20 ml portions of each diluted DP water and 3 ml of $^{85}$Sr work solution without silica colloids. The results were corrected by the same factors used to correct the results obtained from sorption #1 and Sorption #2.
The sorption distribution coefficient (Kdₘ) of ⁸⁵Sr onto colloids of smectite or silica is calculated using the following equation:

\[
Kdₘ = \frac{(γ₀V₀ - γ_i)/M}{γ_j}
\]

where \(γ₀\) is the initial activity of ⁸⁵Sr per milliliter solution, \(V₀\) is the solution volume (ml) in contact with colloidal particles, \(γ_i\) is the total radioactivity of ⁸⁵Sr remaining in the solution after sorption, \(γ_j\) is the radioactivity remaining per milliliter solution, and \(M\) (g) is the mass of colloids used in the sorption process.

**Desorption Procedure**

Strontium-85 loaded colloidal particles were obtained from Sorption #1. At the end of the sorption process, the colloidal particles were separated from liquid by centrifuge. After the wet weights of the colloids were obtained, the colloids were sequentially extracted several times. The extract periods were 10, 20, 30, and 30 days. Each time, 5 ml of Sr-free J-13, DP or DI water was used. The same agitation, centrifuge, and filter procedures used in the sorption experiments were applied. The activity of ⁸⁵Sr in the extracts was measured using the gamma spectroscopy. Accumulated desorption data for 10, 30, 60, and 90 days were reported.

**RESULTS AND DISCUSSION**

**Composition of the Waters**

The natural groundwater from Well J-13 had a pH of 8.2. It contained 1.0 ppm of total organic carbon (TOC), 135 ppm of HCO₃⁻, 30.3 ppm of Si, 46 ppm Na, 13.3 ppm Ca, 1.9 ppm Mg, and 5.4 ppm K. The ionic strength was 0.005 M. The DP groundwater had a pH of 7.9. It contained 109 ppm of HCO₃⁻, 326 ppm Cl, 24.2 ppm Si, 156 ppm Na, 478.2 ppm Ca, 6.1 ppm Mg, and 11.5 ppm K. The ionic strength was 0.016 M. The DI water had a pH of 8.0.
Characterization of Smectite and Silica

The smectite mineral contained 52.0% of SiO₂, 16.2% of Al₂O₃, 1.34% of Fe₂O₃, 0.16% of MgO, 1.88% of CaO, 0.98% of Na₂O, 0.12% of K₂O, and 8.17% of water as well as CO₂ and volatile organic compounds. X-ray diffraction showed that the mineral was smectite. Approximately 92% of smectite colloidal particles was in the size of 0.1 to 0.2 μm and 7.4% of the particles was in the size of > 0.2 μm (Table 1). The surface area of the smectite colloids was 8.33 x 10⁴ m² kg⁻¹. The cation exchange capacity (CEC) was 152.4 Cmol kg⁻¹.

Table 1. Characterization of Smectite and Silica-ST-ZL Colloids

<table>
<thead>
<tr>
<th>Particle size distribution (%)</th>
<th>Smectite</th>
<th>Silica-ST-ZL</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25 nm</td>
<td>0.0</td>
<td>15.5</td>
</tr>
<tr>
<td>25-100 nm</td>
<td>0.0</td>
<td>85.5</td>
</tr>
<tr>
<td>100-200 nm</td>
<td>92</td>
<td>0.0</td>
</tr>
<tr>
<td>200-400 nm</td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td>&gt;400 nm</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Surface Area (m² g⁻¹)</td>
<td>83.3</td>
<td>not measured</td>
</tr>
<tr>
<td>CEC (Cmol kg⁻¹)</td>
<td>152.4</td>
<td></td>
</tr>
<tr>
<td>SiO₂ in colloidal silica stock (%)</td>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>

Manufactured colloidal silica solution of ST-ZL contained 40% of SiO₂ and 60% water. The pH was 9.0. Particle size distribution analyses showed the work solutions of silica ST-ZL contained 85.5% colloidal particles with a size of 25 nm to 100 nm, and 15.5% of the particles were <25 nm (Table 1). Stabilization was achieved by the repulsion between negative charges of particles (12). A test showed that the stability of silica colloidal particles would be 250 years for ST-ZL colloids at solution pH > 7.5 (13).

Sorption of ^{85}Sr onto Colloids of Smectite and Silica

The results obtained from Sorption #1 show that smectite colloids sorbed 92% to 100% of ^{85}Sr in all three waters after 7 days (Figure 1), and the sorption distribution coefficient, Kdₘ
values, ranged from $2.1 \times 10^2$ to $6.0 \times 10^3$ (data not shown). Adsorption of $^{85}$Sr onto silica colloids varied within the three waters. After 7 days, silica colloids sorbed 10% of $^{85}$Sr in DP groundwater, 52% of $^{85}$Sr in Well J-13 water, and 99% of $^{85}$Sr in DI water. The $K_d$ values were $2.4 \times 10^0$, $2.35 \times 10^1$ and $3.1 \times 10^3$, respectively (data not shown).

![Graph showing adsorption of $^{85}$Sr onto smectite and silica colloids in DP Canyon Groundwater, Well J-13 Water and Deionized Water After 7 Days.](image)

**Figure 1.** Percentage of $^{85}$Sr Adsorbed onto Smectite and Silica Colloids in DP Canyon Groundwater, Well J-13 Water and Deionized Water After 7 Days.

The results obtained from Sorption #2 show that the sorption of $^{85}$Sr onto smectite is a rapid process. After 1 hour period, 91% to 98% of $^{85}$Sr was adsorbed. Thereafter, the amount of $^{85}$Sr adsorbed did not change much during the remaining 95 hours (Figure 2). However, adsorption of $^{85}$Sr onto silica colloids is a slow process and varied within the three waters (Figure 3). In DP groundwater, 12% of $^{85}$Sr was adsorbed after 1 hour. Thereafter, the amounts of $^{85}$Sr adsorbed decreased gradually. At the end of the sorption process, 5.4% of $^{85}$Sr was adsorbed. In
J-13 groundwater and DI water, 59% of $^{85}\text{Sr}$ in J-13 water and 66% of $^{85}\text{Sr}$ in DI water was adsorbed during the first 1 hour. After that the amounts of $^{85}\text{Sr}$ adsorbed did not change much during the remaining 95 hours.

![Graph](image)

**Figure 2. Percentage of $^{85}\text{Sr}$ Adsorbed onto Smectite Colloids as a Function of Time in DP Canyon Groundwater, Well J-13 Water, and Deionized Water.**

The results from Sorption #3 show that 99% of $^{85}\text{Sr}$ was sorbed onto silica colloids in the water of 0% DP+100% DI and nanopure water. The amounts of $^{85}\text{Sr}$ adsorbed onto silica colloids decreased from 99% to 12% as the proportions of DP water increased from 0% to 100% (Table 2).
Figure 3. Percentage of $^{85}$Sr Adsorbed onto Silica-ST-ZL Colloids as a Function of Time in DP Canyon Groundwater, Well J-13 Water and Deionized Water.

This suggests that the concentrations of Ca in the water significantly influence the adsorption of $^{85}$Sr onto silica colloids. The silica colloidal particles were spherical. Groups of -SiOH and -OH exist at the surface of the particles when the solution pH is greater than 7.0. Therefore, the negatively charged surface of silica colloidal particles may electrostatically sorb (or bind) positively charged Sr$^{2+}$ ions. At the same time, Ca$^{2+}$ present in DP groundwater may compete with $^{85}$Sr for sorption sites on the surface. This results in a less amount of $^{85}$Sr being adsorbed from DP groundwater than from DI water.

The surface of smectite particles exhibits a negative charge and had a larger CEC (152.4 Cmol kg$^{-1}$). The primary functional groups on the surface of smectite colloidal particles are also OH. Therefore, the negatively charged surface of smectite colloids may electrostatically sorb (or bind) positively charged Sr$^{2+}$ ions. The surface of smectite includes external and internal. As much as 80% of the total surface area of smectite colloids is due to internal surfaces (14). This
Table 2. %$^{85}$Sr adsorbed by Silica Colloids as Affected by the Concentration of Ca in different proportions of DP Groundwater.

<table>
<thead>
<tr>
<th>Proportions of DP Groundwater</th>
<th>pH</th>
<th>Ca Conc. (ppm)</th>
<th>%$^{85}$Sr Adsorbed</th>
<th>Kd$_S$ (ml/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% DP + 100% DI</td>
<td>8.1</td>
<td>&lt;0.01</td>
<td>98.9</td>
<td>4.5 x10$^3$</td>
</tr>
<tr>
<td>25% DP + 75% DI</td>
<td>8.0</td>
<td>119.6</td>
<td>26.9</td>
<td>1.6 x10$^1$</td>
</tr>
<tr>
<td>50% DP + 50% DI</td>
<td>8.0</td>
<td>239.1</td>
<td>16.9</td>
<td>9.2 x10$^0$</td>
</tr>
<tr>
<td>75% DP + 25% DI</td>
<td>8.0</td>
<td>358.7</td>
<td>13.3</td>
<td>7.0 x10$^0$</td>
</tr>
<tr>
<td>100% DP + 0% DI</td>
<td>7.9</td>
<td>478.2</td>
<td>12.0</td>
<td>6.1 x10$^0$</td>
</tr>
<tr>
<td>Nanopure Water</td>
<td>7.1</td>
<td>&lt;0.01</td>
<td>99.1</td>
<td>5.3 x10$^3$</td>
</tr>
</tbody>
</table>

provide a larger number of sorption sites for $^{85}$Sr. The $\text{Sr}^{2+}$ ion in water may easily penetrate into the interlayer of the smectite structure.

Sorption of $^{85}$Sr may be the results of a chemisorption or complexation process, in which the $^{85}$Sr bind to hydroxyl (OH$^-$) groups on the surface of smectite or silica colloids. Assuming that $^{85}$Sr binds to the surface (OH$^-$) groups analogous to aqueous coordination reactions, the sorption of $^{85}$Sr onto smectite colloids can be chemically described by the following equation (5, 15).

$$=\text{SOH}^- + \text{Sr}^{2+} + \text{H}_2\text{O} = =\text{SO-Sr(OH)}^+ + 2\text{H}^+ \quad [2]$$

where $=\text{SOH}$ denotes a surface site, and $=\text{SO-Sr(OH)}^+$ is the complex on the surface sites of smectite colloids. In the case of silica colloids, the surface complexation may occur as followings:

$$=\text{Si(OH)}O^- + \text{Sr}^{2+} + \text{H}_2\text{O} = =\text{SiOSr(OH)}_2^0 + \text{H}^+ \quad [3]$$

According to Kosmulski (5) the inner-sphere complexes on the silica may include $=\text{SiOSr}^{2+}$, $=\text{SiOSr(OH)}^+$, and $=\text{SiOSr(OH)}_2^0$ species.

Desorption of $^{85}$Sr From Colloidal Particles

Desorption of $^{85}$Sr from smectite colloids is much slower than the sorption process. After 90 days, approximately 16.5%, 2.9% and 1.1% of Sr was desorbed from smectite colloids using DP groundwater, J-13, and DI water, respectively (Table 3). After Sr ion being sorbed and
penetrated into interlayer of smectite structure, release of Sr is a very slow process. The Ca\(^{2+}\) present in DP groundwater may exchange with Sr\(^{2+}\) from external and internal surface of smectite, resulting more Sr released into DP water.

Desorption of \(^{85}\)Sr from silica colloids was rapid in DP groundwater and slow using J-13 groundwater and deionized water. After 10 days, 99% of Sr was released using DP groundwater. After 90 days, 100% of \(^{85}\)Sr was desorbed using J-13 water, only 7.4% of Sr was desorbed using DI water (Table 3). The Ca\(^{2+}\) ion present in DP and J-13 groundwater may exchange with Sr, resulting in fast release of Sr into water.

Table 3. Percentage of \(^{85}\)Sr Desorbed from Smectite and Silica Colloids in DP Groundwater, Well J-13 Groundwater and Deionized Water.

<table>
<thead>
<tr>
<th>Time (d)</th>
<th>(^{85})Sr Desorbed from Si-ST-ZL Colloids</th>
<th>(^{85})Sr Desorbed from Smectite Colloids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DP</td>
<td>J-13</td>
</tr>
<tr>
<td>10</td>
<td>99</td>
<td>17.8</td>
</tr>
<tr>
<td>30</td>
<td>100</td>
<td>40.5</td>
</tr>
<tr>
<td>60</td>
<td>---</td>
<td>77.0</td>
</tr>
<tr>
<td>90</td>
<td>---</td>
<td>100</td>
</tr>
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</table>

Our results suggest that Sr transport in surface and groundwater includes two way. One is that the release of Sr from silica and smectite colloids transports with water; the other is clay (e.g., smectite) colloids facilitated the transport of Sr along the flowpath. Strontium transport by clay (e.g., smectite) colloids in groundwater may involve the following mechanism. In porous media, which the colloids with size smaller than the pores may migrate over long distances. O'Melia reported (16) that colloidal particles with sizes ranging from 0.1 \(\mu m\) to 1.0 \(\mu m\) were the most mobile during natural gradient flow through a sandy porous medium, with larger and smaller colloids being preferentially removed.

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