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| <b>Title</b>            | Strontium adsorption and penetration in kaolinite at low Sr <sup>2+</sup> concentration  |
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| <b>Citation</b>         | Soil Science and Plant Nutrition, 63(1), 14-17<br><a href="https://doi.org/10.1080/00380768.2016.1277435">https://doi.org/10.1080/00380768.2016.1277435</a>  |
| <b>Issue Date</b>       | 2017-02-02   |
| <b>Doc URL</b>          | <a href="http://hdl.handle.net/2115/68411">http://hdl.handle.net/2115/68411</a>  |
| <b>Type</b>             | article (author version)   |
| <b>Note</b>             | This is an Accepted Manuscript of an article published by Taylor & Francis in Soil Science and Plant Nutrition on 02 Feb 2017, available online: <a href="http://www.tandfonline.com/10.1080/00380768.2016.1277435">http://www.tandfonline.com/10.1080/00380768.2016.1277435</a> . |
| <b>File Information</b> | Submission-Strontium adsorption and penetration in kaolinite at low Sr <sup>2+</sup> concentration-JSSPN-R2.pdf  |



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# 1                    **Strontium adsorption and penetration in kaolinite at low Sr<sup>2+</sup> concentration**

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## 6                    **Abstract**

7                    Behavior of radioactive Sr<sup>2+</sup> in contaminated soils is an important issue in relation to nuclear  
8                    power plant accidents. The Sr<sup>2+</sup> adsorption on kaolinite and its migration in a kaolinite soil were  
9                    investigated because toxic effects of radioactive Sr<sup>2+</sup> have been found very severe for living  
10                    organisms at low Sr<sup>2+</sup> concentrations. Adsorption isotherms of Sr<sup>2+</sup> on kaolinite at different NaCl  
11                    concentration and pH were obtained by the batch method. The calculated distribution coefficients  
12                    ( $K_D$ ) ranged between 600 and 40000 L kg<sup>-1</sup>, which showed a strong preference for the adsorbed  
13                    phase. The results were used to evaluate the ratio ( $r$ ) of penetration length of Sr<sup>2+</sup> relative to that of  
14                    water in a model kaolinite soil. When the Sr<sup>2+</sup> solution was percolated constantly into the kaolinite  
15                    soil, the penetration of Sr<sup>2+</sup> was delayed strongly at low Sr<sup>2+</sup> concentration due to adsorption. The  
16                    Sr<sup>2+</sup> penetration length was only 0.001 - 0.056 % of the water penetration length at pH 6.5 (0.1-10  
17                    mmol L<sup>-1</sup> NaCl). At pH 4.1 (1 mmol L<sup>-1</sup> NaCl) the effect was about 17 times less than at pH 6.5 (1  
18                    mmol L<sup>-1</sup> NaCl). Under all conditions, the Sr<sup>2+</sup> penetration increased when the Sr<sup>2+</sup> concentration  
19                    increased due to the  $K_D$  decrease. The Sr<sup>2+</sup> isotherms could be fitted well to the Langmuir  
20                    adsorption equation, which indicates that only one site type is involved in the Sr<sup>2+</sup> adsorption.

21                    **Key Words:** Adsorption, distribution coefficient, kaolinite, penetration length ratio, strontium

## 22                    **1. Introduction**

23                    Strontium (Sr)-90 is one product of the radioactive elements of nuclear fuel materials emitting  
24                    beta particles. Its half-life is 29 years, and it is harmful to the human health (Fetter *et al.* 1988).  
25                    During the nuclear power plant accidents in Fukushima, Japan and Chernobyl, Ukraine, large  
26                    amounts of radioactive species, including Sr-90, were released into the environment (Bondarkov  
27                    *et al.* 2011; Steinhauser *et al.* 2013). As the radioactive damage is serious, the environmental fate  
28                    of Sr<sup>2+</sup> must be considered, especially at low Sr<sup>2+</sup> concentrations.

29                    Kaolinite is one of the most ubiquitous phyllosilicates in soils and it has next to the basal

30 plane surface a relatively large edge surface (White and Dixon 2002); therefore,  $\text{Sr}^{2+}$  adsorption  
31 and transport in kaolinite soils deserve specific attention. Some reports consider  $\text{Sr}^{2+}$  adsorption  
32 on kaolinite on the basis of ion exchange (Wahlberg *et al.* 1965; Parkman *et al.* 1998; Bascetin and  
33 Atun 2006; Keçeli 2015).  $\text{Sr}^{2+}$  transport in quartz sand (Rod *et al.* 2010), sediment (Wallace *et al.*  
34 2012) and porous material (Prigiobbe *et al.* 2012) were reported. The fact that the distribution  
35 coefficient provides information on both adsorption and migration of a component, which is the  
36 simplest parameter to characterize the influence of environmental factors on the fate of a pollutant.  
37 Thus, the distribution coefficient has been used to characterize Sr-kaolinite systems (Meyer 1979;  
38 Rafferty *et al.* 1981; Erten *et al.* 1988; Bunde *et al.* 1997; Bascetin and Atun 2006; Rani and  
39 Sasidhar 2012). The distribution coefficient of the Sr - kaolinite system under the given conditions  
40 can be determined when the adsorption isotherm of  $\text{Sr}^{2+}$  on kaolinite is known. Migration of  $\text{Sr}^{2+}$   
41 in kaolinite soil can be conveniently characterized by using the ratio of average penetration length  
42 of  $\text{Sr}^{2+}$  relative to that of water. This ratio is determined by the distribution coefficient and the  
43 solid and solution content in the kaolinite soil (Bolt 1978). The migration of  $\text{Sr}^{2+}$  is retarded  
44 because of the adsorption of  $\text{Sr}^{2+}$  to kaolinite soil. This retardation can be quantified by using the  
45 parameter of distribution coefficient. However, there has been little research of  $\text{Sr}^{2+}$  penetration  
46 length at low  $\text{Sr}^{2+}$  concentration compared with water penetration length.

47 The objectives of the present study are therefore to investigate both the characteristics of  $\text{Sr}^{2+}$   
48 adsorption on kaolinite at different NaCl concentration and pH values with emphasis to low  $\text{Sr}^{2+}$   
49 concentrations and the migration of  $\text{Sr}^{2+}$  in a kaolinite soil under these conditions. The  $\text{Sr}^{2+}$   
50 distribution coefficients were derived and used to describe the  $\text{Sr}^{2+}$  migration. To gain further  
51 insight in the mechanism of the adsorption, the  $\text{Sr}^{2+}$  adsorption results were analyzed with the  
52 Langmuir model. The Langmuir model assumes ideal adsorption behavior in a monolayer and  
53 considers the adsorption capacity as independent parameter and neglects valence effects  
54 (Langmuir 1918; Rani and Sasidhar 2012).

## 55 2. Materials and Experiments

56 The kaolinite from Iriki, Kagoshima, was suspended in deionized water and the fraction with a  
57 diameter less than  $2\mu\text{m}$  was obtained by centrifugation. The obtained fraction was freeze-dried  
58 and stored in a closed container. The sample was characterized by using the X-ray diffraction  
59 apparatus (RINT1200, Rigaku Group of companies, Japan); the kaolinite content was 98.1% and  
60 the alunite content was 1.9%.

61 Three g of kaolinite powder was put in a 400 mL centrifuge bottle, mixed well with 300 mL

62 of 1 mol L<sup>-1</sup> NaCl solution and repeated for three times to reach a complete exchange. The clay  
63 was equilibrated with the prescribed NaCl solution at 0.1, 1 or 10 mmol L<sup>-1</sup>. This process was  
64 repeated until the electrical conductance of the suspension equaled that of the prescribed NaCl  
65 solution at 0.1, 1 or 10 mmol L<sup>-1</sup>. A suitable volume of 0.01 mol L<sup>-1</sup> HCl or NaOH solution was  
66 added to adjust the pH of the Na-Kaolinite suspension to 6.5 or 4.1. The final 10 g L<sup>-1</sup>  
67 Na-kaolinite suspension was kept for further use.

68 The Sr<sup>2+</sup> adsorption experiments were conducted by the batch method using a series of  
69 polypropylene centrifuge tubes. Ten mL of the 10 g L<sup>-1</sup> Na-kaolinite suspension was pipetted into  
70 the centrifuge tube. Subsequently, 20 mL of SrCl<sub>2</sub> solution containing the prescribed NaCl  
71 concentration (0.1, 1 or 10 mmol L<sup>-1</sup>) at prescribed pH (4.1 or 6.5) was added to reach an initial  
72 Sr<sup>2+</sup> concentration in the range 2×10<sup>-3</sup> mmol L<sup>-1</sup> to 6×10<sup>-2</sup> mmol L<sup>-1</sup>. The tubes were shaken for 24  
73 hours at room temperature. The pH of the equilibrium suspension was measured and recorded.  
74 Triplicate runs were performed for all batch experiments.

75 The equilibrium suspensions were centrifuged and the supernatants were gathered to  
76 determine the Sr<sup>2+</sup> concentrations by inductively coupled plasma mass spectrometry (ICP-MS:  
77 PerkinElmer SCIEX-ELAN DRC-e). The adsorbed amount of Sr<sup>2+</sup> on the Na-kaolinite was  
78 calculated by subtracting the amount of Sr<sup>2+</sup> in equilibrium solution from the total amount of Sr<sup>2+</sup>  
79 added initially.

### 80 3. Modeling

#### 81 3.1. Distribution coefficient

82 The distribution coefficient,  $K_D$  (L kg<sup>-1</sup>), describes the distribution of the adsorbate over the  
83 solid phase and the solution phase that can be defined as

$$84 \quad K_D = \frac{Q_{Sr}}{[Sr]} \quad (1)$$

85 where  $Q_{Sr}$  is the adsorbed amount of Sr<sup>2+</sup> on kaolinite (mmol kg<sup>-1</sup>) and  $[Sr]$  is the equilibrium Sr<sup>2+</sup>  
86 concentration in the solution (mmol L<sup>-1</sup>). The larger  $K_D$  is, the stronger is the accumulation in the  
87 adsorbed phase.

#### 88 3.2. Retardation and penetration length ratio

89 Let a certain volume of solution containing a concentration  $[Sr]$  mmol L<sup>-1</sup> of cation Sr<sup>2+</sup> at the  
90 prescribed NaCl concentration and pH feed to per unit area of kaolinite. The distribution ratio,  $R_D$ ,  
91 is a commonly used physical parameter for estimating the retardation of a dissolved pollutant in

92 the case of a solution with pollutant that permeates in a column of soil. Because the retardation is  
93 caused by adsorption,  $R_D$  is related to the partition of the contaminant between the solution and the  
94 solid (adsorbed) phase. As  $K_D$  quantifies the partition,  $K_D$  and  $R_D$  are directly related:

$$95 \quad R_D = K_D \frac{\rho_b}{\theta} \quad (2)$$

96 where,  $\rho_b$  ( $\text{kg L}^{-1}$ ) the bulk density of the kaolinite soil (mass of kaolinite in the column per unit  
97 volume of kaolinite and void) and  $\theta$  the volumetric water content of the column of soil per unit  
98 soil volume in saturated condition ( $\text{L L}^{-1}$  or  $\text{m}^3 \text{m}^{-3}$ ). For the calculations, the soil bulk density of  
99 the hypothetical kaolinite soil has to be assumed to be homogeneous and constant. As the bulk  
100 density of natural soil usually ranges from 1.0 to 1.5  $\text{kg L}^{-1}$ , a kaolinite soil bulk density of 1.25  $\text{kg}$   
101  $\text{L}^{-1}$  is used in this study. From this value, and the density of pure kaolinite of 2.65  $\text{kg L}^{-1}$  (Kuroda  
102 *et al.* 2003), the volume fraction of kaolinite in the soil can be obtained:  $1.25/2.65 = 0.472$ .  
103 Consequently, the volume fraction of solution in the soil equals 0.528 when the kaolinite soil is  
104 saturated and this implies that under these conditions  $\theta$  has reached its maximum value of 0.528.  
105 When only the saturation condition is adopted,  $R_D$  is proportional to  $K_D$  because the  $\theta$  and  $\rho_b$  are  
106 constant.

107 In the saturated column, the average penetration length,  $x_p$ , of  $\text{Sr}^{2+}$  fed into the soil by the  $\text{Sr}^{2+}$   
108 solution is defined by the relation (Bolt 1978):

$$109 \quad x_p = \frac{V_F}{\theta} \frac{1}{1+R_D} \quad (3)$$

110 where  $V_F$  is the feed volume of  $\text{Sr}^{2+}$  solution per  $\text{m}^2$  of soil ( $\text{m}^3/\text{m}^2$ ) and  $\theta$  is the saturated water  
111 content ( $\text{m}^3/\text{m}^3$ ).  $V_F/\theta$  is the average penetration length (m) of water in the soil. The ratio,  $r$ , of the  
112 average penetration length of  $\text{Sr}^{2+}$  to that of water is thus obtained as:

$$113 \quad r = \frac{x_p}{V_F/\theta} = \frac{1}{1+R_D} \quad (4)$$

114 The inverse of  $r$ ,  $1+R_D$ , is the retardation factor which is widely used for analyses of solute  
115 transport in soils.

116 As  $K_D$  is a positive quantity,  $R_D$  is positive and this implies that  $r < 1$  and a small  $r$  implies a  
117 strong  $\text{Sr}^{2+}$  retardation. For large  $R_D$  ( $R_D > 100$ ), i.e., large  $K_D$ ,  $r$  is practically speaking inversely  
118 proportional to  $R_D$ . We can also assume that  $\theta$  is a constant unsaturated volumetric water content.  
119 However, in order to obtain the largest penetration length ratio, the saturated condition is adopted  
120 here.

### 121 3.3. Langmuir model

122 The Langmuir model was used for the adsorption of  $\text{Sr}^{2+}$  on kaolinite as follows:

123 
$$Q_{Sr} = \frac{Q_{Sr,m}K_L[Sr]}{1+K_L[Sr]} \quad (5)$$

124 where  $Q_{Sr}$  (mmol kg<sup>-1</sup>) is the Sr<sup>2+</sup> adsorption,  $Q_{Sr,m}$  (mmol kg<sup>-1</sup>) is the maximum adsorption,  $K_L$  the  
 125 Langmuir adsorption constant (L mmol<sup>-1</sup>) and  $[Sr]$  (mmol L<sup>-1</sup>) is the equilibrium Sr<sup>2+</sup>  
 126 concentration. As the Langmuir model is the theoretically derived adsorption model, we use it for  
 127 the theoretical consideration.

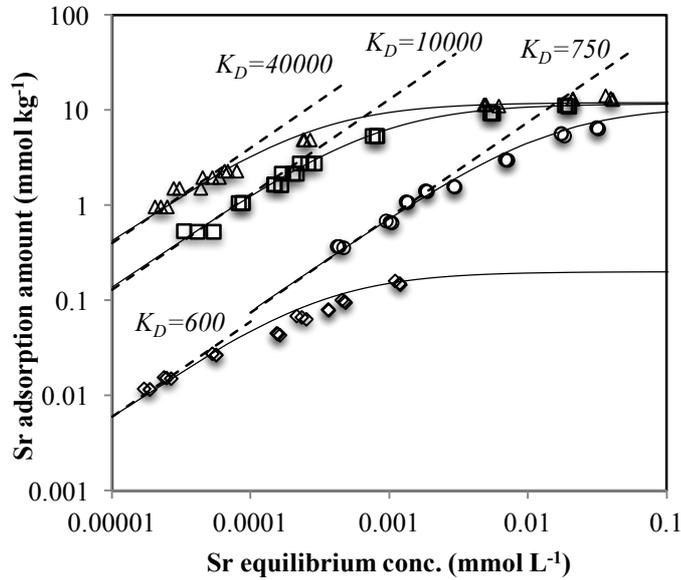
## 128 4. Results and discussion

### 129 4.1. The Sr<sup>2+</sup> distribution coefficient

130 The adsorption isotherms of Sr<sup>2+</sup> on Na-kaolinite at pH 6.5 and pH 4.1 and different NaCl  
 131 concentrations are depicted in Fig. 1 as a double logarithmic plot. The measured adsorption  
 132 increases linearly with slope  $\approx 1$  at low Sr<sup>2+</sup> concentrations, but gradually levels off at higher  
 133 Sr<sup>2+</sup> concentrations. Slope  $\approx 1$  implies a constant adsorption affinity and  $K_D$  value; the low  
 134 concentration ranges for which the slope  $\approx 1$  is the so-called ‘Henry region’; in this range the  
 135 adsorption is directly proportional to the solution concentration, which can be well explained by  
 136 Langmuir model as written in the later part. The dotted lines (slope =1) are lines with different  $K_D$   
 137 (L kg<sup>-1</sup>) as indicated (see Eq.(1)). The constant values of  $K_D$  at low Sr<sup>2+</sup> concentration are observed  
 138 for each isotherm in Fig. 1. They ranged between 600 and 40000 L kg<sup>-1</sup>. The magnitude of  $K_D$   
 139 clearly depends on the solution conditions:  $K_D$  strongly decreases with increasing salt  
 140 concentration and decreasing pH. The  $K_D$  value at low Sr<sup>2+</sup> concentration at 0.1 mmol L<sup>-1</sup> NaCl is  
 141 about 53 times larger than that at 10 mmol L<sup>-1</sup> NaCl. The effect of pH is only investigated at 1  
 142 mmol L<sup>-1</sup> NaCl.  $K_D$  at pH 6.5 is about 17 times larger than  $K_D$  at pH 4.1. Similar effects for the  
 143 kaolinite – Sr<sup>2+</sup> system have been observed by a few researchers (Meyer 1979; Rani and Sasidhar  
 144 2012). For all solution conditions  $K_D$  decreases with increasing Sr<sup>2+</sup> concentrations at Sr<sup>2+</sup>  
 145 concentrations beyond the Henry region, but the Sr<sup>2+</sup> concentration where  $K_D$  starts to decrease  
 146 depends on the solution conditions. Erten *et al.* (1988) and Bascetin and Atun (2006) also  
 147 observed a decrease of  $K_D$  with the increasing Sr<sup>2+</sup> concentration for kaolinite. Concluding this  
 148 section, it is clear that pH and Na<sup>+</sup> concentration influence the adsorption of Sr<sup>2+</sup> on kaolinite and  
 149 the Sr<sup>2+</sup> distribution coefficient strongly.

150 The fittings of the Sr<sup>2+</sup> adsorption data to the Langmuir equation are presented in Fig.1 as  
 151 double logarithmic plot (solid lines). The measured values of Sr<sup>2+</sup> adsorbed on kaolinite are quite  
 152 well fitted to the Langmuir model. The adsorption affinity or Langmuir constant,  $K_L$ , and the  
 153 adsorption capacity,  $Q_{Sr,m}$ , are collected in Table 1. The values of  $K_L$  are strongly influenced by

154 NaCl concentration because the influence of competition between  $\text{Sr}^{2+}$  and  $\text{Na}^+$  on  $K_L$  differs with  
 155 different  $\text{Na}^+$  concentration. Thus,  $K_L$  obtained in this study should be interpreted as a *conditional*  
 156 *constant*;  $Q_{\text{Sr},m}$  are almost identical under different NaCl concentration.



157  
 158 **Fig. 1**  $\text{Sr}^{2+}$  adsorption isotherms on kaolinite at two pH values and three salt concentrations. The dotted  
 159 lines are lines of equal distribution coefficient ( $K_D$ ) and the solid lines are fitting curves of Langmuir  
 160 model. The symbols are measured values. At pH 6.5:  $\triangle$  0.1  $\text{mmol L}^{-1}$  NaCl,  $\square$  1  $\text{mmol L}^{-1}$  NaCl,  $\circ$   
 161 10  $\text{mmol L}^{-1}$  NaCl. At pH 4.1:  $\diamond$  1  $\text{mmol L}^{-1}$  NaCl

162 **Table 1** Langmuir isotherm parameters

| <i>pH</i> | Na conc. | $Q_{\text{Sr},m}$ | $K_L$ | $R^2$ |
|-----------|----------|-------------------|-------|-------|
|           | 10       | 11.0              | 60    | 0.990 |
| 6.5       | 1        | 11.6              | 1100  | 0.995 |
|           | 0.1      | 12.0              | 3300  | 0.987 |
| 4.1       | 1        | 0.2               | 2500  | 0.934 |

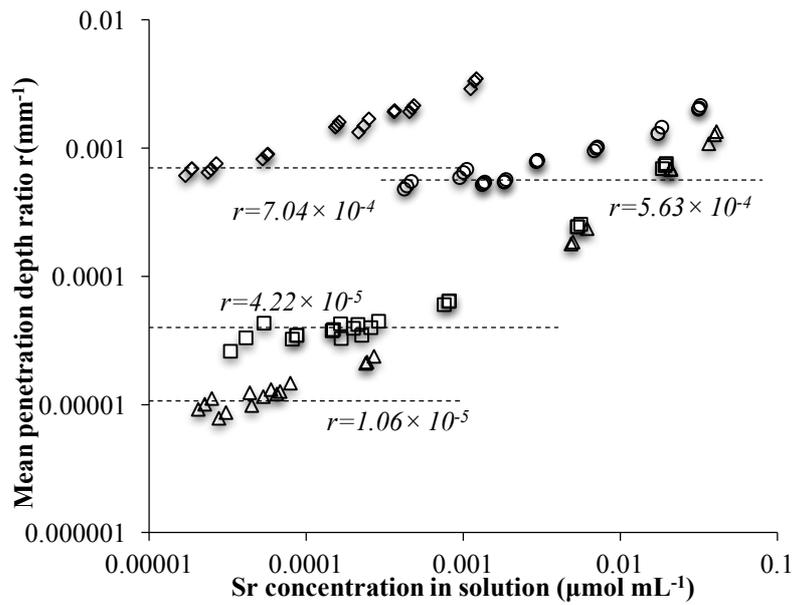
163 By comparing  $K_D$  and  $K_L$  at given solution conditions, it should be noted that  $K_L$  is a constant  
 164 for all  $\text{Sr}^{2+}$  concentrations, but that  $K_D$  is only constant in the Henry region. The difference is due  
 165 to the fact that Eq.(5) takes into account the adsorption capacity,  $Q_{\text{Sr},m}$ . At relatively high  $\text{Sr}^{2+}$   
 166 concentration the probability of adsorption is decreased by the decrease of the vacant sites for  $\text{Sr}^{2+}$   
 167 adsorption. Eq.(5) takes this decreased probability into account, while Eq.(1) does not take the  
 168 adsorption capacity into account. At sufficiently low  $\text{Sr}^{2+}$  concentration ( $K_L[\text{Sr}] \ll 1$ ) Eq.(5)  
 169 reduces to the Henry equation,  $Q_{\text{Sr}} = Q_{\text{Sr},m} K_L [\text{Sr}]$ , and this relation equals Eq.(1) with  $Q_{\text{Sr},m} K_L = K_D$ ,

170 indicating that in the Henry region  $K_L$  and  $K_D$  are closely related.

171 The  $\text{Sr}^{2+}$  isotherms could be fitted well to the Langmuir adsorption equation, which indicates  
172 that only one site type is involved in the  $\text{Sr}^{2+}$  adsorption. The values of  $K_D$  keeping constant at low  
173  $\text{Sr}^{2+}$  concentration were observed. Therefore, even if the  $\text{Sr}^{2+}$  concentration is extremely lower  
174 than those in this experiment, the values of  $K_D$  in the Henry region can be valid from the  
175 theoretical viewpoint. The value can be applicable for the Sr-90 contaminated sites where the  $\text{Sr}^{2+}$   
176 concentration is supposed to be very low.

#### 177 4.2. The $\text{Sr}^{2+}$ penetration length ratio

178 The average penetration length ratio  $r$ , representing the average penetration length of  $\text{Sr}^{2+}$  relative  
179 to that of water is depicted in Fig. 2 as a function of the equilibrium  $\text{Sr}^{2+}$  concentration of the  
180 solution fed in the kaolinite soil. The four depicted data sets correspond with the four-adsorption  
181 isotherms depicted in Fig. 1. Since the ratio  $r$  is inversely proportional to  $(1+R_D)$  and  $R_D$  is  
182 proportional to  $K_D$ , the large  $K_D$  values corresponding with the isotherms at low  $\text{Sr}^{2+}$  concentration  
183 induce small  $r$  values. As  $K_D$  increased with decreasing NaCl concentration and increasing pH, the  
184 reverse trend should be observed for  $r$  and this explains the decrease of  $r$  with decreasing NaCl  
185 concentration and increasing pH observed in Fig. 2. The small values of  $r$  indicate considerable  
186 retardation of  $\text{Sr}^{2+}$  upon solution penetration in the kaolinite soil. The increase of the penetration  
187 length ratio of  $\text{Sr}^{2+}$  in kaolinite with increasing  $\text{Sr}^{2+}$  concentration is due to the decrease of  $K_D$ . By  
188 considering the above trends quantitatively, the following observations can be made. The  
189 dependence of the penetration length ratio of  $\text{Sr}^{2+}$  in kaolinite on pH is considerable: at  $1 \text{ mmol L}^{-1}$   
190 NaCl and low  $\text{Sr}^{2+}$  concentration, the  $r$  value at pH 4.1 ( $7.04 \times 10^{-4}$ ) is 16.7 times larger than  $r$  at pH  
191 6.5 ( $4.22 \times 10^{-5}$ ). It is favorable for  $\text{Sr}^{2+}$  adsorption at high pH, which results in a strong retardation  
192 of  $\text{Sr}^{2+}$  in sediments (Wallace *et al.* 2012) and iron oxides (Prigiobbe *et al.* 2012). The effect of the  
193 NaCl concentration at pH 6.5 and low  $\text{Sr}^{2+}$  concentration on the penetration length of  $\text{Sr}^{2+}$  is also  
194 large: at  $0.1 \text{ mmol L}^{-1}$  NaCl  $r$  equals  $1 \times 10^{-5}$  which is 53.3 times smaller than  $r$  at  $10 \text{ mmol L}^{-1}$   
195 NaCl ( $5.63 \times 10^{-4}$ ). The trend of the present results corresponds well with literature results. Wallace  
196 *et al.* (2012) have reported that for sediments the presence of  $\text{Na}^+$  resulted in the much lower  
197 sorption of  $\text{Sr}^{2+}$  which caused a significant migration of  $\text{Sr}^{2+}$  in the sediments. Hull *et al.* (2008)  
198 have reported that  $\text{Sr}^{2+}$  transported rapidly in the vadose zone sediment at high  $\text{Na}^+$  concentration  
199 and the  $\text{Sr}^{2+}$  mobility decreased significantly in the absence of competing cations.



200

201 **Fig.2** The penetration length ratio of  $\text{Sr}^{2+}$  versus the fed solution concentration  $\text{Sr}^{2+}$ . The dotted lines  
 202 and indicated  $r$  values are the penetration ratios corresponding with the largest  $K_D$  values at low  $\text{Sr}^{2+}$   
 203 concentration for each solution condition. At pH 6.5:  $\triangle$  0.1  $\text{mmol L}^{-1}$  NaCl,  $\square$  1  $\text{mmol L}^{-1}$  NaCl,  $\circ$  10  
 204  $\text{mmol L}^{-1}$  NaCl. At pH 4.1:  $\diamond$  1  $\text{mmol L}^{-1}$  NaCl

205 The evaluated penetration length ratios of the  $\text{Sr}^{2+}$  at low  $[\text{Sr}]$  are very small. The  $\text{Sr}^{2+}$   
 206 penetration length is about 0.001% of the water penetration length at the conditions of pH 6.5, 0.1  
 207  $\text{mmol L}^{-1}$  NaCl and  $[\text{Sr}] < 5 \times 10^{-8} \text{ mmol L}^{-1}$ . At pH 6.5, 1  $\text{mmol L}^{-1}$  NaCl and  $[\text{Sr}] < 2 \times 10^{-7} \text{ mmol}$   
 208  $\text{L}^{-1}$ , the value is about 0.004%. At pH 6.5, 10  $\text{mmol L}^{-1}$  NaCl and  $[\text{Sr}] < 2 \times 10^{-6} \text{ mmol L}^{-1}$ , the value  
 209 is 0.056 %. At pH 4.1, 1  $\text{mmol L}^{-1}$  NaCl and  $[\text{Sr}] < 2 \times 10^{-8} \text{ mmol L}^{-1}$ , the value is about 0.07 %.  
 210 These values clearly indicate that  $\text{Sr}^{2+}$  is most strongly retarded by kaolinite at low NaCl  
 211 concentration and relatively high pH.

212 The values of extremely low penetration length ratio of  $\text{Sr}^{2+}$  relative to that of water in  
 213 kaolinite were calculated theoretically based on the distribution coefficient obtained from  
 214 adsorption experiment. Although there are many complicated factors affecting the migration of  
 215  $\text{Sr}^{2+}$  in soils such as preferential flow, the average penetration length in the soils with uniform soil  
 216 structure can be predicted.

217 In conclusion, because only one site type is involved in the  $\text{Sr}^{2+}$  adsorption in the kaolinite,  
 218 the constant values of  $K_D$  are valid to calculate the average penetration length of  $\text{Sr}^{2+}$  even at  
 219 extremely low  $\text{Sr}^{2+}$  concentration theoretically. The low values of average penetration length ratio  
 220 show the strong retardation in kaolinite soils for  $\text{Sr}^{2+}$  at low  $\text{Sr}^{2+}$  concentration. Although the  
 221 penetration ratio is a simple and useful parameter to estimate the mobility of  $\text{Sr}^{2+}$ , direct

222 observations of Sr<sup>2+</sup> migration in soil are also necessary to confirm the theoretically calculated  
223 retardation.

## 224 **Acknowledgments**

225 The authors would like to express gratitude to China Scholarship Council (CSC) for supporting  
226 Zigong Ning's oversea study. This research was supported by Grants-in-Aid for Scientific  
227 Research (No. 25252042) from the Japan Society for the Promotion of Science.

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