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JOURNAL OF  
ENVIRONMENTAL  
RADIOACTIVITY

Journal of Environmental Radioactivity 79 (2005) 39–53

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## Radiocaesium fallout behaviour in volcanic soils in Iceland

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Received 2 December 2003; received in revised form 10 May 2004; accepted 17 May 2004

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### Abstract

The retention of  $^{137}\text{Cs}$  in various types of Andosols in Iceland was investigated. Soils were sampled at 29 sites with varying precipitation and environmental conditions. Samples were obtained from 0 to 5, 5 to 10, and 10 to 15 cm depths. The amount of radiocaesium present was quite variable, ranging between 300 and 4800  $\text{Bq m}^{-2}$  and correlated closely to total annual precipitation ( $r^2 = 0.71$ ). The majority of  $^{137}\text{Cs}$ , 82.7% on average, was retained in the uppermost 5 cm of the soil. The greatest penetration of  $^{137}\text{Cs}$  was observed for organic Histosols (76.3% in top 5 cm). The Icelandic Vitrisols (barren, poorly developed Andosols) are coarse grained with only 2–5% clay content and contain little organic matter (< 1%). Yet these soils retained 74% of  $^{137}\text{Cs}$  in the top 5 cm. The results indicate that radiocaesium fallout is strongly retained by colloidal materials characteristic of Andosols, such as allophane and ferrihydrite. Most soils in Iceland are subject to severe and prolonged freezing and waterlogging; despite this,  $^{137}\text{Cs}$  is retained in the upper soil horizons and vertical migration is negligible in Icelandic Andosols. However, erosion and aeolian activity can markedly influence the amount and vertical distribution of radiocaesium in Icelandic soils.

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*Keywords:* Iceland; Radiocaesium fallout;  $^{137}\text{Cs}$ ; Andosols; Soil; Allophane

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## 1. Introduction

Radiocaesium in Icelandic ecosystems originated primarily from nuclear weapon tests carried out in the atmosphere until the early 1960s. The fallout reached a maximum in about 1965. Additional fallout from the Chernobyl accident in 1986 was minor in Iceland (Palsson et al., 1994). Measurements of radiocaesium fallout in precipitation in Iceland began in 1958. To date, measurements of radiocaesium in soils have been confined to a few locations in Iceland. The present study is the first comprehensive attempt to determine the amount of radiocaesium present and its retention characteristics in Icelandic soils.

Numerous studies on radiocaesium retention and mobility in different soil types have been published (e.g., Arnalds et al., 1989; Livens and Loveland, 1988; Arapis et al., 1997; Schuller et al., 1997; Maes et al., 1999; Staunton and Levacic, 1999; Waegeneers et al., 1999; Facchinelli et al., 2001). The results of these studies indicate that radiocaesium behaviour in soils is controlled by several physical, chemical, and environmental factors such as pH, cation exchange capacity (CEC), organic carbon content, animal activity, soil texture and type of clay minerals. Radiocaesium extraction experiments reveal that clays are the most important binding agent of radiocaesium in mineral soils, but radiocaesium is generally more mobile in organic than in clayey soils (e.g., Barber, 1964; Valcke and Cremers, 1994; Rigol et al., 2002; Staunton et al., 2002).

The caesium ion has a very short radius of hydration, and is more strongly adsorbed to cation exchange sites of clays than other common ions such as  $\text{Ca}^{++}$ ,  $\text{K}^+$ ,  $\text{Mg}^{++}$  and  $\text{Na}^+$  (e.g., Sposito, 1989). The most effective clay minerals in retaining radiocaesium in soils are 2:1 layer-type phyllosilicates such as illite, vermiculite and smectite. The  $\text{Cs}^+$  ions are firmly bound on highly selective interlayer sites in illite and vermiculite and are not easily remobilised in soils containing these clays (e.g., Tamura, 1964; Sawhney, 1972; Coughtrey and Thorne, 1983; Comans et al., 1991).

Soils that form in volcanic tephra (ash) materials are termed Andosols in the WRB soil classification legend (FAO, 1998). Andosols tend to accumulate appreciable amounts of organic matter, often  $>6\%$  C (e.g., Nanzyo et al., 1993), which also affects their chemical behaviour and ion retention. The dominant clay minerals of Andosols are allophane, imogolite and ferrihydrite, often referred to as “short-range order minerals”. These minerals and organic matter in Andosols have both permanent and pH dependent charge (variable charge).

Few studies have been conducted on caesium retention in Andosols. Two notable studies are by Cox and Fankhauser (1984), who studied the geographical distribution of fallout  $^{137}\text{Cs}$  in volcanic soils in Hawaii, and by Schuller et al. (1997, 2002), who related climatic conditions and soil properties to  $^{137}\text{Cs}$  retention in volcanic soils in Chile. Chorover et al. (1999) reported that short-range order minerals had strong  $\text{Cs}^+$  retention in young and intermediate soils formed in basaltic volcanic materials in Hawaii.

Studies on the behaviour of  $^{137}\text{Cs}$  in natural environments are important in understanding its dynamics and uptake into agricultural products, and to make

plans in the event of nuclear accidents. In this paper, caesium retention will be examined in relation to chemical and mineralogical properties of Andosols in Iceland. Both spatial and vertical distribution of radiocaesium fallout in Icelandic soils is examined, and the possible effect of environmental conditions such as erosion, aeolian deposition and rainfall pattern is considered.

## 2. Background

### 2.1. Geology

Iceland is a volcanic island located in the North Atlantic Ocean. The island is situated on the spreading Mid-Atlantic Ridge, which marks the boundary between the North American and the Eurasian tectonic plates. The volcanic activity in Iceland is largely confined to the rift zones that cut through the country. Geologically, Iceland is young, with the oldest exposed rocks dating to early Miocene (~20 m.y.). The present day landscape has mostly been created by the Pleistocene glaciers, carving out valleys and fjords and leaving glacial deposits on the surface (Saemundsson, 1980; Johannesson and Saemundsson, 1998).

Volcanic eruptions are common in Iceland. Since the settlement of Iceland in late 9th century AD at least 200 eruptions have occurred. In postglacial time about 90% of the volcanic products were basaltic and 10% intermediate and acidic in composition. About 11% of the surface area is covered with postglacial lavas. Explosive eruptions, producing tephra, are common in Iceland as many volcanic systems are partially covered by glaciers or submerged by water (Thorarinsson and Saemundsson, 1980).

### 2.2. Andosols, volcanic soils

The parent materials of Icelandic soils are largely of volcanic origin, and most of the soils are classified as Andosols according to the FAO classification (Arnalds, 2004). Iceland has the largest area of Andosols in Europe, and ca. >5% of all Andosols in the world.

Andosols have unique properties that separate them from other soil types of the world (see e.g., Wada, 1985; Kimble et al., 1999). Among these properties are exceptionally high water retention (sometimes exceeding 100% at 1.5 MPa tension, i.e. more weight of water than dry soil), rapid infiltration rates and hydraulic conductivity, carbon accumulation, high P-retention, low bulk density (often  $<0.7 \text{ g cm}^{-3}$ ) and lack of cohesion. The soils often have a high cation exchange capacity (CEC) which is pH dependent and increases rapidly with pH. These properties are caused by the types of colloids that form in the soils, which constitute both clay minerals and metal-humus complexes. The clay minerals are poorly crystallized (short-range order), such as allophane, imogolite, and ferrihydrite that form from rapid weathering of tephra, which causes high concentrations of Al, Si, and Fe in the soil solution. When the pH is  $<5$ , the Al forms stable complexes with organic matter instead of co-precipitating with Si as clay minerals. Considerable quantities of organic matter can

accumulate in this manner (often >6%). The boundary between Andosols and organic Histosols is therefore set at 20% C (FAO, 1998) instead of the 12% mark commonly applied. Allophane also forms bonds with organic matter by ligand exchange, causing carbon accumulation in the soils. The high carbon content of the soils and high surface area of clay minerals give rise to high CEC of Andosols, which is important for ion retention in the soils, including retention of caesium.

### 2.3. Soil formation and soil classes

During the Quaternary period, Iceland was nearly fully glaciated. Since then, the surface has largely been mantled by aeolian sediments and numerous tephra layers, forming the parent materials of Icelandic soils.

During the last ~1500 years, catastrophic erosion has removed a substantial part of the soils that had formed in the aeolian and tephra sediments. This erosion has created large barren deserts with unstable surfaces that act as sources for aeolian sediments during dry storm events (see Arnalds, 2000; Arnalds and Kimble, 2001). Desert areas now cover >40,000 km<sup>2</sup> or >40% of the country. Depositional rates close to unstable sandy areas commonly exceed 1 mm year<sup>-1</sup>. The combination of a steady flux of volcanic aeolian materials and frequent minor tephra deposition events (forming layers <10 mm thick) has a major influence on soil formation. The chemical composition and morphology of these materials are varied, ranging from solid basalt glass particles to rhyolitic pumice grains.

The rate of aeolian and tephra deposition varies considerably depending on distance from volcanoes and unstable sources of aeolian materials. This distance has a major effect on soil forming processes, with a lower pH and greater C accumulation as the distance from these sources increases, but higher pH and more rapid allophane formation where aeolian materials steadily recharge the soil system. The soils do not contain phyllosilicates, except for minor amounts in the glacial till (Wada et al., 1992), and in soils furthest away from the desert areas (Arnalds and Kleber, unpublished data).

Icelandic soils have been divided into soil classes in a recently developed classification by the Agricultural Research Institute (Arnalds, 2004; [www.rala.is/desert](http://www.rala.is/desert)). The most common categories are *Histosols* (organic soils, C > 20%), *Histic Andosols* (C = 12–20%), *Gleyic Andosols* (Andosols of wetlands, 1–12% C), *Brown Andosols* (freely drained allophanic Andosols, C = 1–12%), and *Vitrisols*, which are various soil types of Icelandic desert surfaces. The Vitrisols have low organic content (<1% C), and relatively lower contents of allophane and ferrihydrite than the Gleyic Andosols and Brown Andosols.

## 3. Materials and methods

### 3.1. Sampling

The study is based on 33 soil cores, collected from 29 sites in 2000–2001 (Fig. 1, Table 1). The sampling sites were distributed to represent most geographic regions of

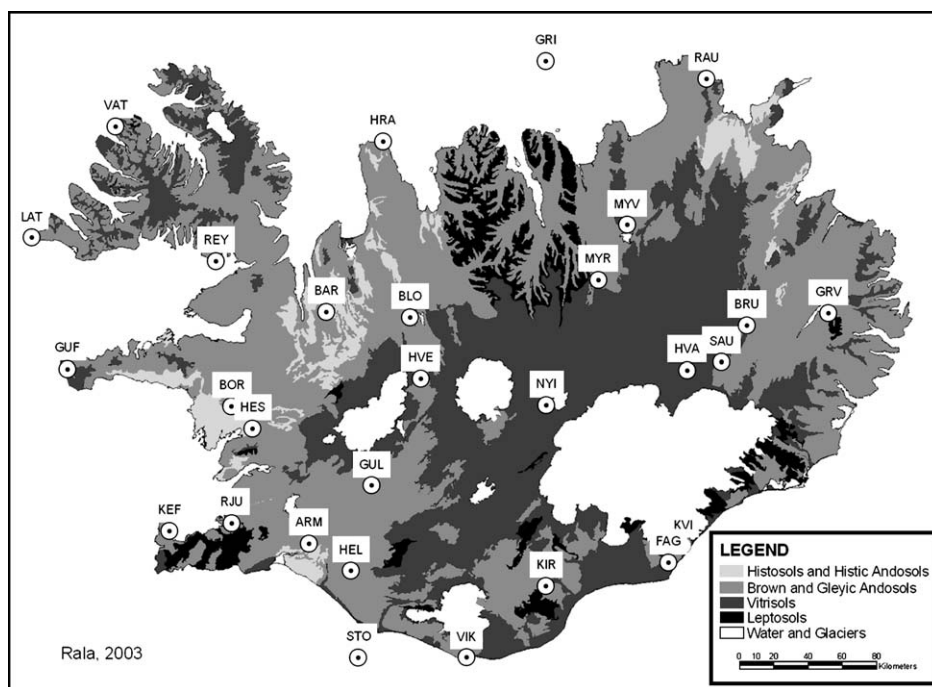


Fig. 1. Location of sampling sites for the period 2000–2001. Vitrisols and Leptosols are the main sources of aeolian material in Iceland. (The relative distance of sampling sites from aeolian sources is shown in Table 1.)

Iceland, geology, soils and amount of precipitation. To obtain reliable precipitation data the sampling sites were selected close to meteorological stations, where possible. Twenty-five meteorological stations operating since 1960 or earlier were chosen.

Each sample was made by compositing 20 cores obtained by a soil probe. The probe is 19 mm in diameter. The cores were cut into 5 cm thick slices and then pooled for 0–5, 5–10 and 10–15 cm depth intervals. Cores were collected 1 m apart along a 20 m long transect. Some characteristics of the soils were described, such as horizonation, Munsell colours and soil texture by hand.

### 3.2. Analysis

The samples were dried in a slow-airflow cabinet at 40 °C and then homogenized and sieved through a 2-mm mesh sieve. The activity concentration of  $^{137}\text{Cs}$  was measured using Ortec HPGe gamma detectors of 48.6% and 55.4% relative efficiency for the 1.33 MeV peak of  $^{60}\text{Co}$ . Uncertainties in the activity measurements were below 4%. The  $^{137}\text{Cs}$  activity present was calculated on per unit area basis in  $\text{Bq m}^{-2}$ .

Soil pH was measured in 1:2.5 soil to water solution (Van Lagen, 1996). Organic carbon was determined by dry combustion by Leco CR12 apparatus. CEC was measured by replacing cations with ammonium acetate at pH 7, with subsequent

Table 1  
Description of sampling sites

Sampling site	Sample id.	Elevation (m a.s.l.)	Soil type	$^{137}\text{Cs}$ (Bq m $^{-2}$ ) (total)	Annual precipitation (mm year $^{-1}$ ) <sup>a</sup>	Mean annual temperature (°C) <sup>b</sup>	Relative distance from aeolian sources <sup>c</sup>
Barkarstadir	BAR	114	Histosol	1085	437	1.8	4
Blondulón	BLO	460	Brown Andosol	977	< 600		2
Bru in Jokuldalur	BRU	386	Brown Andosol	1099	507	0.7	2
Fagurhólsmyri (three samples) <sup>d</sup>	FAGa	46	Vitrisol	4680	1809	4.6	1
	FAGb		Vitrisol	4827			
	FAGc		Vitrisol	4714			
Grimsarvírkjún	GRV	95	Brown Andosol	1252	643	3.1	4
Grimsey	GRI	15	Histic Andosol	1206	704	2.3	4
Gufuskalar	GUF	7	Gleyic Andosol	2375	~ 1200		2
Gullfoss	GUL	135	Brown Andosol	2144	1058		2
Storhofdi in Heimaey	STO	118	Brown Andosol	2549	1374	4.8	2
Hella	HEL	20	Gleyic Andosol	2927	1052	3.7	3
Hestur <sup>e</sup>	HES	20	Gleyic Andosol	1478	823	3.3	4
Hraun at Skagi	HRA	3	Histosol	746	430	2.5	4
Hvannalindir	HVA	640	Vitrisol	3806	< 400		1
Hveravellir (two samples) <sup>f</sup>	HVEa	641	Brown Andosol	2192	769	-1.2	1
	HVEb		Vitrisol	885			
Keflavík	KEF	40	Brown Andosol	1997	960	4.4	2
Kirkjubaejarklaustur	KIR	32	Gleyic Andosol	3623	1589	4.5	2
Kvisker <sup>g</sup>	KVI	30	Brown Andosol	4763	3192		2
Latrabjarg	LAT	35	Brown Andosol	2227	958		3
Myrar	BOR	100	Histic Andosol	1559	~ 800		3
Myri	MYR	295	Brown Andosol	928	381		2
Myvatn	MYV	285	Brown Andosol	805	406	1.4	1
Nyidalur	NYI	800	Vitrisol	1945	~ 1000		1
Raufarhofn	RAU	5	Gleyic Andosol	626	666	2.0	2
Reykholar	REY	27	Histosol	848	510		4
Rjupnahaed	RJU	120	Brown Andosol	1691	870	4.3	2

Table 1 (continued)

Sampling site	Sample id.	Elevation (m a.s.l.)	Soil type	$^{137}\text{Cs}$ (Bq m $^{-2}$ ) (total)	Annual precipitation (mm year $^{-1}$ ) <sup>a</sup>	Mean annual temperature (°C) <sup>b</sup>	Relative distance from aeolian sources <sup>c</sup>
Saudardalur (two samples)	SAUa	600	Brown Andosol	1299	<i>~700</i>		1
	SAUb		Vitrisol	305			
Stora Arnot	ARM	20	Brown Andosol	3966	1232		2
Vatnadalur	VAT	30	Histic Andosol	2955	959	3.4	4
Vik in Myrdalur <sup>h</sup>	VIK	200	Brown Andosol	4367	2010	5.2	2

<sup>a</sup> Average annual precipitation for the period 1960–1967. Values given in italic are estimates from a precipitation map for the period 1931–1960 (Sigfusdottir, 1965).

<sup>b</sup> Mean annual temperature for the period 1961–1990.

<sup>c</sup> Nos. 1 and 2, sites located within or close to aeolian sources; nos. 3 and 4, sites located outside aeolian sources (see Fig. 1).

<sup>d</sup> Precipitation data from 1961 to 1967.

<sup>e</sup> Precipitation data from 1964 to 1967 (Hvanneyri).

<sup>f</sup> Precipitation data from 1966 to 1973.

<sup>g</sup> Precipitation data from 1962 to 1967.

<sup>h</sup> Precipitation data from 1965 are missing.

replacement of  $\text{NH}_4$  by NaOH (Van Lagen, 1996). Ammonium oxalate extraction is the most common method for the determination of short-range order minerals in volcanic soils, such as allophane and ferrihydrite. This solution preferentially dissolves the poorly crystallized materials with much less or minimal effect on well crystallized minerals (e.g., Wada, 1989; Dahlgren, 1994). The soils were extracted by ammonium oxalate in the dark using a method outlined by Blakemore et al. (1987) and Al, Si, and Fe ( $\text{Al}_o$ ,  $\text{Si}_o$  and  $\text{Fe}_o$ ) were determined in the extracted solution by ICP-OES (inductively coupled plasma optical emission spectrometry). Allophane content was obtained by multiplying  $\text{Si}_o$  by a factor of 6 (Parfitt, 1990), and ferrihydrite by multiplying  $\text{Fe}_o$  by 1.7 (Parfitt and Childs, 1988). Total clay was obtained by combining allophane and ferrihydrite.

All soil analyses were done on duplicate samples, with additional measurements if the difference was  $> 10\%$  between the first two determinations.

A Kruskal–Wallis test (critical level of significance  $p = 0.05$ ) was used to assess differences in  $\% \text{ }^{137}\text{Cs}$  in top 5 cm of the soil. The tests were performed by StatView, version 5.0.1 (SAS Institute Inc., Cary, NC, USA).

## 4. Results and discussion

### 4.1. Soil properties

In Table 2, the properties of the soils are summarised for the top 5 cm. The spatial distribution of the soil classes is presented in Fig. 1. The Histosols have high contents of organic matter, but low clay content. They are found distant from active aeolian sources, indicated in the last column of Table 1. Vitrisols are the dominant soil type of the barren highland areas and in the vicinity of glacial plains, where aeolian sources are widespread. Soil pH, measured in water, is relatively low for the organic soils, but is considerably higher in the Vitrisols. The soil at Fagurholmsmyri (FAG) is formed in rhyolitic tephra at the surface under high rainfall, which leads to lower pH compared to the pH of Vitrisols in Iceland in general. The slow chemical weathering of silicious tephra and reduced release of basic cations, results in relatively low clay content at the FAG site (i.e. 4.2–5.5%). The CEC of the soils is high as is common for Andosols (Nanzyo et al., 1993), and is mostly related to the organic content of the soil, and also in part to the clay content, especially where the organic content is low.

Radiocaesium activity concentrations in the soils showed considerable variation, from  $300 \text{ Bq m}^{-2}$  to  $4800 \text{ Bq m}^{-2}$  (Table 1). According to a model proposed by UNSCEAR (2000), a radiocaesium deposition density of about  $1.3 \text{ kBq m}^{-2}$  might be expected at the time of sampling in the  $60^\circ$ – $70^\circ$  N latitude zone. In our study an average value of about  $2.0 \text{ kBq m}^{-2}$  was obtained.

### 4.2. Radiocaesium and annual precipitation

The range in  $^{137}\text{Cs}$  content is mostly explained by variation in annual precipitation (Fig. 2,  $r^2 = 0.71$ ;  $p < 0.0001$ ). However, two desert sites show the greatest deviation



Table 2  
Soil properties

Soil type	pH (in water)	Organic carbon (%)	CEC (meq/100 g)	Clay <sup>a</sup>
Vitrisol ( <i>n</i> = 7)	4.9–7.9 (6.3)	0.2–6.1 (2.3)	6.0–55.6 (16.6)	4.2–11.9 (6.6)
Brown Andosol ( <i>n</i> = 15)	5.3–6.5 (5.7)	3.9–12.0 (7.8)	9.7–35.8 (23.8)	2.7–17.4 (11.7)
Gleyic Andosol ( <i>n</i> = 5)	5.2–6.1 (5.6)	7.9–16.4 (12.4)	23.0–37.7 (30.7)	12.5–26.7 (19.1)
Histic Andosol ( <i>n</i> = 3)	4.7–5.7 (5.3)	17.7–28.7 (23.3)	36.4–43.4 (40.4)	2.1–13.8 (7.9)
Histosol ( <i>n</i> = 3)	4.2–5.7 (4.9)	28.3–32.8 (29.9)	15.0–65.5 (41.9)	3.6–9.8 (6.5)

Range of values and averages (in parentheses).

<sup>a</sup> Allophane + ferrihydrite.

from the precipitation–<sup>137</sup>Cs relationship. The first one is the Hvannalindir site (HVA), located in the sandy desert of the Northeast highlands. This anomaly could possibly be caused by the addition of extra aeolian material containing <sup>137</sup>Cs and by snow accumulation into the gentle depression where the sample was taken. The lowest <sup>137</sup>Cs was measured at Saudardalur (SAUb). The soils at this site are characterized by calcareous sand on a hillside. A large proportion of the precipitation most likely runs off the site and we hypothesize that much of the <sup>137</sup>Cs deposited on these soils is not retained. If these two sites are not included an improved regression coefficient of 0.88 ( $p < 0.0001$ ) is obtained. Other data are not considered to deviate that much from the expected value to warrant further consideration.

Similar trends have been found in other volcanic regions such as in Hawaii (Cox and Fankhauser, 1984) and Chile (Schuller et al., 2002). Cox and Fankhauser (1984)

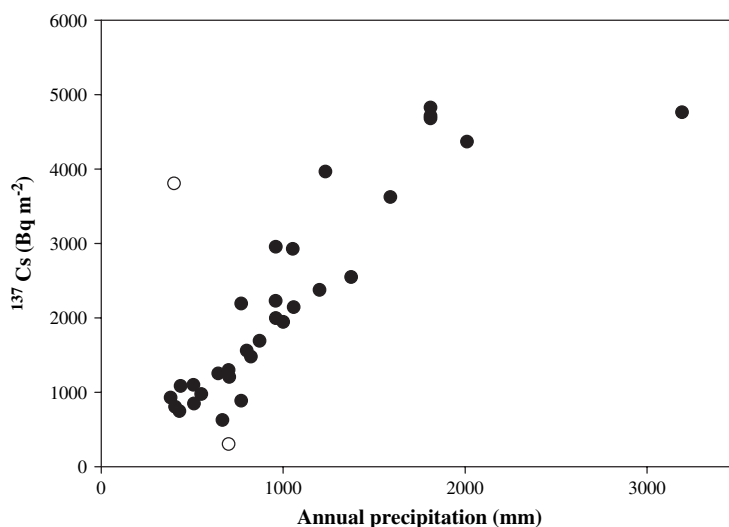


Fig. 2. Relationship between <sup>137</sup>Cs activity concentration in soils and annual precipitation. When the two outliers (open circles) (HVA and SAUb, which are deserts with active aeolian processes) are omitted, then the  $r^2$  improves from 0.71 to 0.88.

concluded that radiocaesium concentrations in Hawaiian soils were mainly controlled by mean annual rainfall. In Chile, based on 29 soil samples, a regression coefficient of 0.79 was obtained between radiocaesium deposition and precipitation (Schuller et al., 2002). In countries with other soil types, such as Germany (Bunzl and Kracke, 1988); Montana, USA (Arnalds et al., 1989); Canada (Blagoeva and Zikovskiy, 1995) and Korea (Lee and Lee, 1997), positive correlations have also been reported. The regression coefficients ( $r^2$ ) from these studies generally range between 0.6 and 0.8.

The highest radiocaesium levels were found in Southeast Iceland, where annual precipitation reaches >3000 mm, but the lowest levels were found in North Iceland with the average annual precipitation as low as 400 mm. The sampling strategy with a large number of cores gathered for each sample, and the location of sites near meteorological monitoring stations ensure that the close link between precipitation and radiocaesium fallout is well expressed.

#### 4.3. Vertical distribution of radiocaesium

The majority of the radiocaesium fallout is retained in the uppermost 5 cm of the soil – 82.7% on average (Table 3; Fig. 3). Below 15 cm depth, the radiocaesium contents were less than 2% of the total in the Brown Andosols and Histic Andosols. The greatest penetration of radiocaesium observed was about 25 cm, at site FAGa. This clearly indicates that caesium fallout is generally strongly retained by colloidal materials in Icelandic soils. Schuller et al. (2002) reported deeper penetration of  $^{137}\text{Cs}$  down to 65 cm in volcanic soils at Hapludands in Chile.

The  $^{137}\text{Cs}$  retention in the top 5 cm did not differ significantly among soil types (nonparametric Kruskal–Wallis test,  $n = 7, 15, 5, 3, 3$ ). However, there were some indications of slightly different retention characteristics with a tendency to the strongest retention in Histic Andosols (89.2% in top 5 cm; three sampling sites), Brown Andosols and Gleyic Andosols (85.7% in top 5 cm; 20 sampling sites) compared with the organic Histosols (76.3% in top 5 cm; three sampling sites) and Vitrisols (74% in top 5 cm; seven sampling sites). This trend is expressed by a box-plot in Fig. 3. The median values are high while low values for surface  $^{137}\text{Cs}$  retention for Vitrisols lower the mean considerably. The strong retention of  $^{137}\text{Cs}$  at the surface of Icelandic soils is attributed to the presence of both clay minerals in the soils (predominantly allophane and ferrihydrite), and organic matter (bound by allophane, metal–humus complexes and a variety of organic materials). The strong retention of radiocaesium by the coarse textured Vitrisols is noteworthy (74% in top 5 cm). The

Table 3  
Depth distribution of  $^{137}\text{Cs}$  (% of total) according to soil type

Soil type	Number of sites	0–5 cm depth	5–10 cm depth	10–15 cm depth
Vitrisol	7	74.0	18.7	5.6
Brown Andosol	15	85.7	11.9	1.7
Gleyic Andosol	5	85.8	10.3	3.0
Histic Andosol	3	89.2	7.9	1.8
Histosol	3	76.3	14.4	6.0

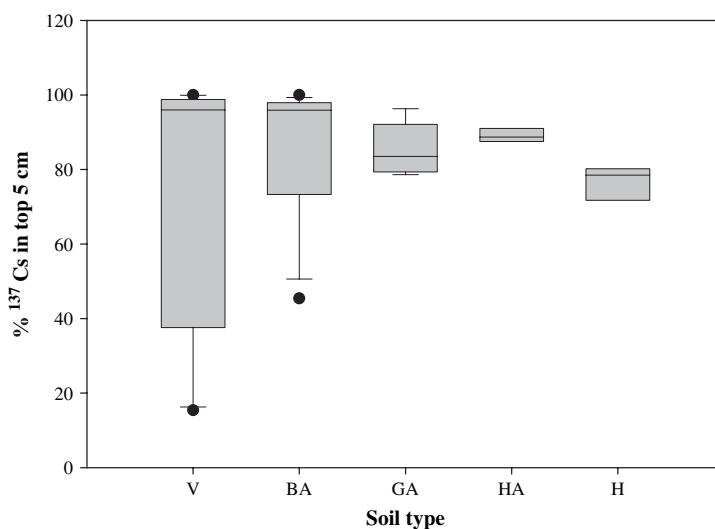


Fig. 3. Box-plot for  $^{137}\text{Cs}$  retention in the top 5 cm. V: Vitrisol, BA: Brown Andosol, GA: Gleyic Andosol, HA: Histic Andosol, H: Histosol. The box shows the median (long horizontal line) and values between the 25 and 75% percentiles. The short horizontal lines label the 10 and 90% percentiles, but points mark highest and lowest values (V and BA).

clay content of the Vitrisols is relatively low at 4.2–12%, and substantial retention in these soils indicates strong  $^{137}\text{Cs}$  absorption capacity of allophane and ferrihydrite.

The range of radiocaesium retention in Icelandic soils in the top 5 cm (74–89%) is comparable to values reported in other European countries. In soils from Sweden, UK, Luxembourg, Bohemia, Hungary and Italy, usually more than 80% of the total  $^{137}\text{Cs}$  inventory is found in the top 10 cm of the soils (Livens et al., 1991; Rosen et al., 1999; Szerbin et al. 1999; Hölgye and Maly, 2000; Dahm et al., 2002). Generally,  $^{137}\text{Cs}$  retention is related to the clay minerals of these soils, especially illite and micaceous clays. In spite of different clay mineralogy of Andosols, similar retention pattern is observed, with  $^{137}\text{Cs}$  effectively bound by allophane and ferrihydrite.

An additional factor influencing the surface retention of  $^{137}\text{Cs}$  in Icelandic soils is the formation of ice in the soils during winter, which significantly reduces water conductivity (see Orradottir, 2002), and can also cause rapid runoff during winter storms and thawing events. Others have made this observation, such as Schuller et al. (1997) who noted that in Antarctic regions the length of the annual thawing and freezing periods plays an important role in radionuclide migration in a range of soil types.

Cation exchange capacity reflects the total amount of active colloidal materials in the soils, both clays and organic matter. The results show that the amount of  $^{137}\text{Cs}$  retained below the 5 cm depth is not related to the CEC, and therefore explanations for this deviation need to be sought elsewhere. Analyses of other soil factors do not explain the variation either, with no statistical relationship between  $^{137}\text{Cs}$  retention in the top 5 cm and % C, annual precipitation or pH.

Rapid aeolian deposition is a likely explanation for the presence of significant levels of  $^{137}\text{Cs}$  below the 5 cm depth where it occurs (e.g., HVA, MYR, and possibly FAGa). The caesium containing materials are gradually becoming buried under continuous aeolian deposition caused by wind erosion in the vicinity. Surface runoff at sites receiving high amounts of precipitation also contributes to relatively lower surface retention at the KVI and STO sites (i.e. 62.7% and 50.6%, respectively).

Although animal activity in the soil surface has been cited as a factor leading to redistribution of fallout  $^{137}\text{Cs}$  to greater depths (e.g., Arnalds et al., 1989), burrowing animals, which have the potential to affect the  $^{137}\text{Cs}$  distribution in soils, are absent in Iceland. Another constraint to vertical transport is that Icelandic soils do not form large cracks which allow for rapid percolation of water.

Gerzabek et al. (1997) concluded that radiocaesium migration in Alpine regions is largely controlled by climatic factors, such as the short vegetation period, freezing of soil profiles and waterlogging. The Histosols, Histic Andosols and Gleyic Andosols we sampled tend to be waterlogged through extended periods of the year, especially in winter and early spring. Most soils in Iceland are subject to severe and prolonged freezing and waterlogging; despite this  $^{137}\text{Cs}$  is retained in the upper soil horizons and vertical migration is negligible in Icelandic Andosols.

Sites showing signs of surface water flow were avoided during this study. As the sites sampled are not forested, snow tends to be blown from the point of deposition to accumulate in depressions or long distances from where the snow was deposited. This lateral movement may cause deviation from the  $^{137}\text{Cs}$ –rainfall relationship. Nevertheless, the relationship was surprisingly strong in the study, despite the possible effects of snow-drift, winter ice and thaw events.

## 5. Conclusions

Icelandic Andosols retain  $^{137}\text{Cs}$  effectively in the soils. All the soils, including those with low clay content (Vitrisols), retain most of the radiocaesium at the surface, indicating strong retention capacity of the clay constituents of these soils, which are mostly allophane and ferrihydrite. Organic materials are also believed to provide exchange sites that retain  $^{137}\text{Cs}$ .

The strong surface retention seems not to be markedly affected by waterlogging and seasonal freezing at the sampling sites. Deeper penetration of  $^{137}\text{Cs}$  at some sites is generally not explained by soil factors, but rather external factors such as rapid aeolian deposition, and surface runoff from sites with excessive rainfall. Other aspects of the environment, such as winter ice in the soil, types of ice crystals, snow-melt, and snow-drift may also be important locally, but the sampling scheme was not designed to reveal such inferences. The strong preservation of  $^{137}\text{Cs}$  in the surface reflects limited activity of burrowing animals. Furthermore the soils do not form large cracks upon drying, which prevents crack-flow of precipitation into deeper parts of the soils.

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