Solid/liquid partition coefficients (K_d) and plant/soil concentration ratios (CR) for selected soils, tills and sediments at Forsmark

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Abstract

Solid/liquid partition coefficients (K_d) are used to indicate the relative mobility of radionuclides and elements of concern from nuclear fuel waste, as well as from other sources. To indicate the uptake of radionuclides in biota concentration ratios (CR) between soil and biota are used. This report summarized K_d data for regolith and marine sediments based on concentrations of 69 indigenous stable elements measured from samples collected at the Forsmark site and CR data concerning cereals growing on these soils. The samples included 50 regolith samples from agricultural land and wetlands, 8 samples of till collected at different depths, and two marine sediment samples. In addition, cereal grains, stems and roots were collected from 4 sites for calculation of CRs.

The regolith samples represented the major 5 deposits, which can be used as arable land, at the site (clayey till, glacial clay, clay gyttja and peat (cultivated and undisturbed)). K_d values were generally lower for peat compared to clay soils. There were also clear differences in K_d resulting from differences in soil chemistry within each regolith type. Soil pH was the most important factor, and K_d values for many elements were lower in acidic clay soils compared to basic clay soils.

Although there were only a few samples of sandy till and marine sediment, the K_d values were generally consistent with the corresponding regolith K_d values.

Of the different cereal parts the grain always had the lowest CR. In most cases, the root CR was significantly higher than the grain CR, whereas only for a few elements were the grain and stem CR values different.

Sammanfattning

Fördelningskoefficienter (K_d) används för att indikera den relativa rörligheten för radionuklider och ämnen från radioaktivt avfall, liksom från andra källor. För att indikera upptaget av radionuklider i biota används koncentrationskvoter (CR) mellan jord och biota. Den här rapporten summerar K_d data för 69 stabila ämnen som mätts i prover av regolit och marina sediment från Forsmarksområdet samt CR data från säd som växt på dessa jordar. Proverna inkluderar 50 regolitprover från jordbruksmark och våtmarker, 8 moränprover hämtade på flera olika djup, samt två marina sedimentprover. Dessutom insamlades ax, strån och rötter från säd från 4 platser för beräkning av CR.

Regolitproverna representerar de 5 huvudsakliga avlagringar som kan användas som jordbruksmark i området (lerig morän, glaciallera, lergyttja and torv (brukad och orörd)). K_d-värdena var oftast lägre för torv än för lerjordar. Det fanns också uppenbara skillnader i K_d beroende på de olika regoliternas kemiska egenskaper. Den viktigaste faktorn var pH och för många ämnen var K_d-värdena lägre i sura lerjordar jämfört med i basiska lerjordar.

Även om antalet sandiga moränprover och marina sedimentprover var få var K_d-värdena generellt överensstämmande med motsvarande K_d-värden för regolitproverna.

När det gäller sädesproverna hade alltid axen de lägsta CR-värdena. I de flesta fall var CR för rötter signifikant högre än motsvarande CR för ax och endast för ett fåtal ämnen skilde sig CR för ax och strån från varandra.

Contents

1 Introduction

1.1 Background

In order to take care of the low and intermediate waste generated during dismantling of closed nuclear facilities in Sweden an extension of the existing facility for low and intermediated radioactive waste, SFR (Slutförvaret för kortlivat radioaktivt avfall), is planned. The SFR facility is situated at the coast of the Baltic Sea in the vicinity of the Forsmark power plant. This report is a background report for the safety assessment, SR-PSU, which will be included in the permit application for the extension of the SFR facility.

For the long term safety assessment the transport and uptake of radionuclides in the future landscape of Forsmark is important. Potential releases of radionuclides from the extended SFR facility might reach the surface in groundwater discharge areas. These discharge areas will be situated in lakes, wetlands and in low-lying areas that could be used as arable land. These low-lying areas that can be used as arable land are therefore of great importance to the safety assessment and have been the focus of this study. To model the possible transport of radionuclides in the discharge areas, the chemical and physical properties of regolith from these areas must be determined as well as the behaviour of different element in terms of sorption and uptake. This report presents the results from an extensive site investigation where regolith of arable land, till samples from different depths, marine sediment and cereals grown on the arable land have been analysed.

Extensive site investigations have been conducted in the Forsmark area since 2002 (Lindborg 2008) with the objective being to site a geological repository for spent nuclear fuel. The site investigations began in 2002 and were completed in 2007 and thanks to these site investigations a detailed description of the regolith of the Forsmark area site including the spatial distribution of the Quaternary deposits and soil types, together with the physical and chemical properties of the deposits is available in Hedenström and Sohlenius (2008).

At present all known regolith in the Forsmark area was formed during the Quaternary period. Most of the regolith was deposited at the end and after the latest glaciation. The properties of the regolith are consequently an effect of the shifting environments that have taken place during that period. Till is the oldest of these deposits and was deposited during the latest glaciation. The till is unsorted with respect to grain size and consists of all grain sizes from clay particles to boulders. The till in the coastal region of northern Uppland contains calcite emanating from Ordovician limestone situated north of the area. Calcite is easily dissolved by chemical weathering. However, the area has only been above the sea level for a relatively short period and weathering has not had time to dissolve all the calcite present in the till. As a result, soils developed on these materials have relatively high pH.

After the latest deglaciation (about 10,800 years ago), Uppland was completely situated below the level of the Baltic Sea. Most of north-eastern Uppland was below sea level until a few thousand years ago. Shortly after the deglaciation thick layers of glacial clay were deposited at the floor of the Baltic Sea. The deposition of clay continued during the thousands of years that north-eastern Uppland was covered by the Baltic Sea. These postglacial clays often contain organic material and are referred to as gyttja clay or clay gyttja. The clays are often situated in the lowest parts of the landscape, which are potential discharge areas for groundwater. Both the glacial and postglacial clays are often used as arable land.

At present peat is accumulating in the many wetlands situated in north-eastern Uppland. Peat consists almost entirely of organic material from the plants that lived in the wetlands. Some peat-covered wetlands have been drained to obtain arable land.

In most of the Forsmark area the till has a relatively high content of stones and boulders and is therefore used for forestry rather than agriculture. In parts of the area the till has a high content of clay and this part is more commonly used as arable land. A relatively small proportion of the area is presently used as arable land. In the future the present sea floor will be uplifted as an effect of the isostatic rebound. The land areas that can be used for cultivation will then increase significantly and different types of regolith (loose deposits) can then be used as arable land.

Based on the available knowledge of the regolith of the Forsmark area four different types of regolith suitable as arable land can be distinguished in the Forsmark area and its surroundings: 1) clayey till, 2) glacial clay, 3) clay gyttja and 4) peat. The last three of these deposits are often situated in potential or actual discharge areas for groundwater. The four deposits have entirely different individual properties due to varying mineralogy, grain size composition and content of organic material.

1.2 Solid/liquid partition coefficients, K_d

Solid/liquid partition coefficients (K_d) or 'distribution coefficients', are commonly used to estimate the mobility and distribution of elements in the environment (Gil-García et al. 2009a, b, Vandenhove et al. 2009a). The K_d values are empirical and represent a very simplistic model of sorption or attenuation on soil or sediment solids. Key features of K_d that need to be recognized are:

- The K_d is the ratio of the concentration of an element on a solid phase (soil or sediment) divided by the equilibrium concentration in the contacting liquid phase (water).

- K_d implies a linear, zero-intercept relationship between sorbed and non-sorbed species of the element, and that the sorption is at equilibrium and is reversible. These assumptions are commonly disproven (e.g. Loffredo et al. 2011), but the errors associated with using these simplifying assumptions are generally considered no worse than the uncertainties and complexities associated with alternative models of attenuation. Any lack of fit of the simple K_d model to the real system becomes part of the overall uncertainty in the values of K_d. Typical 95th percentile uncertainty bands for K_d data are 25-fold above and below the central value (Sheppard 2005).

- Attenuation mechanisms other than simple sorption, such as chemical precipitation, incorporation into insoluble organic molecules, occlusion by surface coatings and diffusion into micropores, are included in an empirical measure of K_d.

- In general, all isotopes of an element are assumed to have the same K_d value, because sorption is a chemical property generally unaffected by atomic mass or nuclear emissions. The possible exceptions are low atomic mass elements where the mass differences affect kinetically limited processes (e.g. Lemarchand et al. 2007), and decay progeny of nuclides where alpha recoil may impact release of mineral-bound elements (e.g. Sheppard et al. 2008).

- K_d values are highly dependent on environmental factors, including but not limited to pH, redox condition, particle size distribution, organic matter content, biological activity and temperature.

- Because K_ds are ratios, by the Central Limit Theorem the data tend to be lognormally distributed (this is the appropriate default assumption), and so the geometric mean (GM) and geometric standard deviation (GSD) are the most common summary statistics. Similarly, statistical analysis is usually of log-transformed data or of data transformed to be non-parametric.

- There are two commonly used units of measure for K_d, either L kg^{-1} or m^3 kg^{-1}, these are 1000-fold different in value. The latter is the more correct SI (Le Système International d'Unités) unit.

- K_d is used to estimate leaching of elements through deposits, and since variation in K_d can have both positive and negative effects on radiological dose estimates, it is not simple nor advisable to bias the selection of best estimates higher or lower to achieve 'conservative' or 'more-safe' values.

1.3 Concentration ratios, CR

In the modelling of migration of radionuclides in different environments the uptake in vegetation is commonly described by concentration ratios (CRs, e.g. Carini 2009, Vandenhove et al. 2009b). As with K_d, CR is also empirical and represents a very simplistic model of uptake. Key features of CR that need to be recognized are:

- The CR is the ratio of the concentration of an element in a specified part of the vegetation (often the edible part) divided by the concentration in the solid phase of the soil, assuming steady state conditions.

- The CRs describe the uptake of elements at steady state conditions, assuming that uptake will increase or decrease proportional to the increase/decrease in substrate concentration. The assumption is not valid for all element and plants (Simon and Ibrahim 1987). For non-essential elements, where the uptake is a passive process governed by concentration differences, the assumption can be considered valid, but for essential elements where the uptake is an active process this is not always true. The uptake of essential elements will be affected by the substrate concentration up to a certain level. At this level the need for the element in biota is satisfied and no increase in the active uptake will take place even if the substrate concentration will increase (Vera et al. 2003). This phenomenon is most certainly valid also for non-essential elements with properties resembling those of a specific essential element (e.g. Sr which resembles Ca).

- CR values generally differ with different soil characteristics and with different plant species, its properties (Greger 2004) and the part of the plant that is of concern (Bettencourt et al. 1988).

- In general, all isotopes of an element are assumed to have the same CR value, because uptake is a process generally unaffected by small deviations in atomic mass or nuclear emissions.

- Because CRs are ratios, by the Central Limit Theorem the data tend to be lognormally distributed (this is the appropriate default assumption), and so the geometric mean (GM) and geometric standard deviation (GSD) are the most common summary statistics.

- The commonly used unit of measure for CR is kg dw (soil) kg dw^{-1} (plant).

- Since higher CR values indicate higher uptake in vegetation and vice versa it is possible to bias the selection of parameter values in order to use conservative values. In the SKB models, the amount of the radionuclide present within the vegetation is not numerically extracted from the soil pool in the model, thus preventing underestimation of exposure by other exposure pathways (e.g. external exposure or future vegetation uptake).

1.4　Objectives

There are important sources of generic K_d values for soil and sediments, e.g. IAEA (2010), Gil-García et al. (2009a, b), Vandenhove et al. (2009a), Sheppard (2011), which makes it possible to derive K_d values pertinent to most sites. However, because K_d values are empirical, there is an inevitable requirement to obtain K_d data from the site under consideration. The objective of this study was to extend the already existing K_d database from earlier site investigations conducted in the Forsmark area by Swedish Nuclear and Waste Management Company. In comparison to earlier studies this study focuses on K_d values measured for selected soil types which are representative of the deposits that may be utilised for agricultural purposes in the Forsmark area in the future. The sampled deposits are situated in the north-eastern Uppland, within an area of 30 km from the site where the repository is planned to be built (see map in Figure 2-1.). When sampling regolith from agricultural lands, it was possible to acquire plant samples from the same sites, and so the corresponding plant/soil CRs are reported in addition to K_d.

In order to investigate how the regolith K_d values vary with depth the study was extended to also include till samples collected from two deep trenches in the Forsmark area.

Another issue of interest was the implication of the pre-treatment of the soil samples on the analysis results. When estimating K_d for deposits, the measurements should reflect the equilibrium of reversible sorption processes and using a strong extraction media could lead to overestimated K_d values for a few elements. No definitive protocol has been established but according to Sheppard et al. (2009) the preferred method is to use aqua regia extraction of the solid phase. In an earlier K_d study performed for SKB (Engdahl et al. 2008) lacustrine and marine sediment samples where totally dissolved using a nitric/hydrochloric/hydrofluoric acid mixture followed by $LiBO_2$ fusion. For a more correct use of these data a comparison of the two preparation methods was performed on marine sediment from the Forsmark area.

2 Methods

2.1 Field methods

Four regolith types identified as potential arable types in the future Forsmark area were sampled. The sampled regolith types were clayey till, glacial clay, clay gyttja and peat. The peat samples were either from cultivated areas (named cultivated peat samples) or from undisturbed wetlands (named wetland peat samples). The peat in the wetlands has different properties in comparison to the cultivated peat and was therefore sampled separately, giving a total of five sampled regolith types. Not all of these deposits are presently cultivated in the Forsmark area. Some of the deposits were therefore sampled at other locations in north-eastern Uppland (see Figure 2-1). In addition to these samples, 8 samples of sandy till were taken from different depths in two machine-dug trenches in order to evaluate the difference between surface and subsurface soils. The sampled till have not been used for agricultural purposes. Two marine sediment cores were also taken during the sampling campaign in order to investigate the effect of different analysis methods. For the sampling sites where crops were grown at the time of sampling, the crops were also collected. In total, five crop samples were collected from four sites. The regolith samples are listed in Table 2-1 and the crop samples are listed in Table 2-2. The location of each sampling site is shown in Figure 2-1.

Table 2-1. Sampled regolith at the investigated sites. The coordinates are stored in SKB's database SICADA.

Sample id	Regolith type	Depth	Comment
AFM001362	Clay gyttja	20–25 cm	
AFM001362	Clay gyttja	50–55 cm	
AFM001365	Clay gyttja	20–25 cm	
AFM001365	Clay gyttja	50–55 cm	
AFM001367	Clay gyttja	20–25 cm	
AFM001367	Clay gyttja	50–55 cm	
AFM001368	Clay gyttja	20–25 cm	
AFM001368	Clay gyttja	50–55 cm	
AFM001356	Clayey till	20–25 cm	
AFM001356	Clayey till	50–55 cm	
AFM001357	Clayey till	20–25 cm	
AFM001357	Clayey till	50–55 cm	
AFM001359	Clayey till	20–25 cm	
AFM001359	Clayey till	50–55 cm	
AFM001361	Clayey till	20–25 cm	
AFM001361	Clayey till	50–55 cm	
AFM001376	Clayey till	20–25 cm	
AFM001376	Clayey till	50–55 cm	
AFM001363	Glacial clay	20–25 cm	Classified as clay gyttja in field, but after analyses it was re-assigned as glacial clay
AFM001363	Glacial clay	50–55 cm	Same as above
AFM001369	Glacial clay	20–25 cm	
AFM001369	Glacial clay	50–55 cm	
AFM001371	Glacial clay	20–25 cm	
AFM001371	Glacial clay	50–55 cm	
AFM001372	Glacial clay	20–25 cm	
AFM001372	Glacial clay	50–55 cm	
AFM001373	Glacial clay	20–25 cm	
AFM001373	Glacial clay	50–55 cm	
AFM001374	Glacial clay	20–25 cm	
AFM001374	Glacial clay	50–55 cm	
AFM001379	Peat-cultivated	20–25 cm	
AFM001379	Peat-cultivated	50–55 cm	

Sample id	Regolith type	Depth	Comment
AFM001381	Peat-cultivated	20–25 cm	
AFM001381	Peat-cultivated	50–55 cm	
AFM001382	Peat-cultivated	20–25 cm	
AFM001382	Peat-cultivated	50–55 cm	
AFM001383	Peat-cultivated	20–25 cm	
AFM001383	Peat-cultivated	50–55 cm	
AFM001384	Peat-cultivated	20–25 cm	
AFM001384	Peat-cultivated	50–55 cm	
AFM001385	Peat-wetland	20–25 cm	
AFM001385	Peat-wetland	50–55 cm	
AFM001387	Peat-wetland	20–25 cm	
AFM001387	Peat-wetland	50–55 cm	
AFM001388	Peat-wetland	20–25 cm	
AFM001388	Peat-wetland	50–55 cm	
AFM001389	Peat-wetland	20–25 cm	
AFM001389	Peat-wetland	50–55 cm	
AFM001391	Peat-wetland	20–25 cm	
AFM001391	Peat-wetland	50–55 cm	
PFM007690_1	Sandy till	180 cm	Trench 2, Western part, southern wall
PFM007691_2	Sandy till	350 cm	Trench 2, Mid part, northern wall
PFM007692_1	Sandy till	50 cm	Trench 2, Easternmost part
PFM007692_2	Sandy till	100 cm	Trench 2, Easternmost part
PFM007693_1	Sandy till	30 cm	Trench 2, Easternmost part
PFM007693_2	Sandy till	100 cm	Trench 2, Easternmost part
PFM007694_1	Sandy till	250 cm	Trench 1, Northern wall
PFM007694_2	Sandy till	250 cm	Trench 1, Northern wall
PFM006045_1	Marine sediment	0–5 cm	
PFM006045_2	Marine sediment	0–5 cm	
PFM006045_1	Marine sediment	20–25 cm	
PFM006045_2	Marine sediment	20–25 cm	

Table 2-2. Sampled crops at the investigated sites.

Sample id	Crop type	Regolith type
AFM001367 C	Barley grain	Clay gyttja
AFM001367 D	Barley stem	Clay gyttja
AFM001367 E	Barley root	Clay gyttja
AFM001372 C	Wheat grain	Glacial clay
AFM001372 D	Wheat stem	Glacial clay
AFM001372 E	Wheat root	Glacial clay
AFM001372 F	Barley grain	Glacial clay
AFM001372 G	Barley stem	Glacial clay
AFM001372 H	Barley root	Glacial clay
AFM001373 C	Barley grain	Glacial clay
AFM001373 D	Barley stem	Glacial clay
AFM001373 E	Barley root	Glacial clay
AFM001376 C	Barley grain	Clayey till
AFM001376 D	Barley stem	Clayey till
AFM001376 E	Barley root	Clayey till
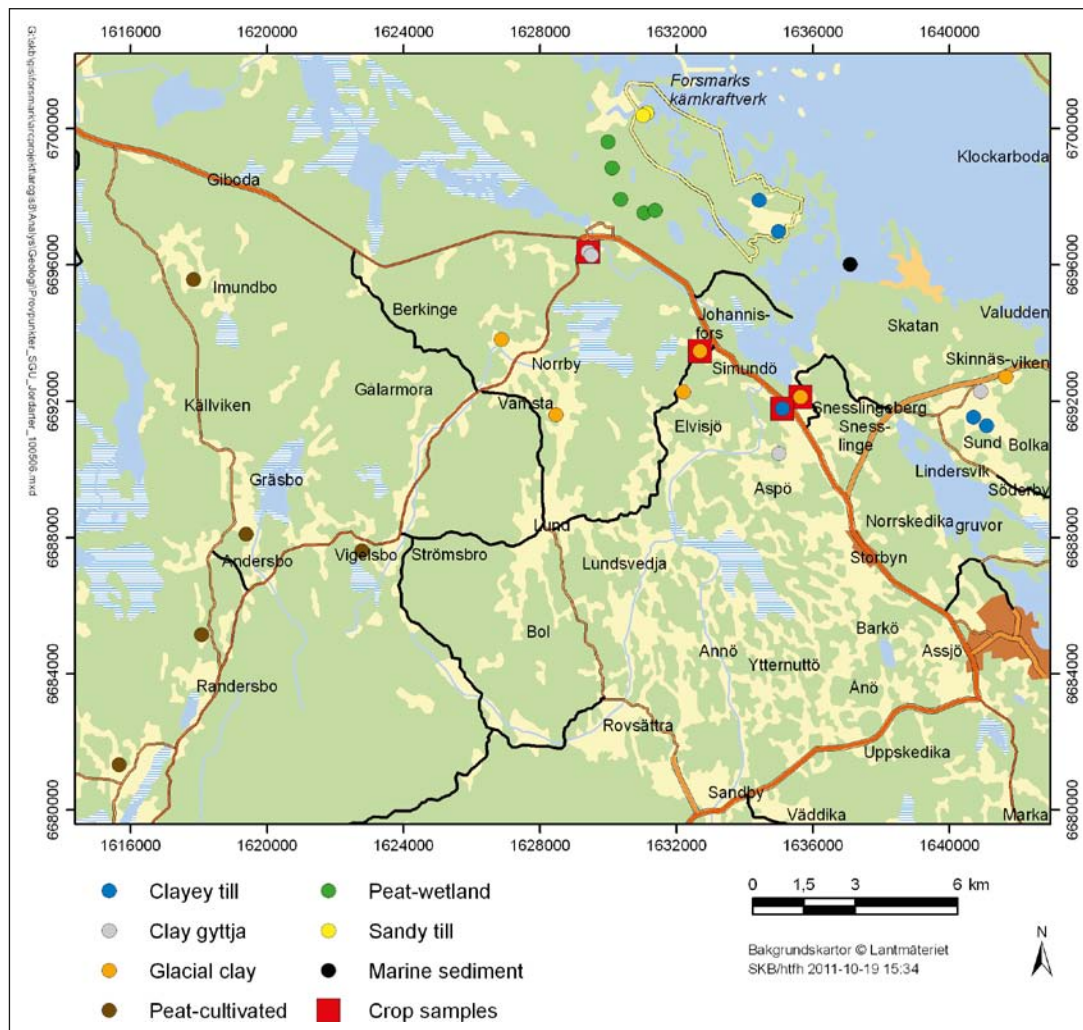
Figure 2-1. *The sampling sites of this study.*

2.1.1　Sampling of regolith of arable lands and wetlands

The map of Quaternary deposits from the Geological Survey of Sweden (SGU) and maps from Lantmäteriet (the Swedish mapping, cadastral and land registration authority) were used to identify cultivated areas and wetland sites with the different deposits.

For each of the five regolith types at least six possible sampling sites were identified. During the field work, in August 2010, five sampling sites from each type of regolith were chosen (altogether 25 sites). Table 2-1 shows the identification numbers and type of regolith at the sampled sites. After sampling, one soil that in the field was identified as clay gyttja (AFM001363) was basic in pH and differed in other characteristics as well. This soil was re-assigned as glacial clay. The coordinates of the sites are stored in the SKB database 'SICADA'. At every site, samples were taken from five sampling positions. One middle sampling position was first identified. Thereafter four other sampling positions were identified 10 m to the north, south, east and west of the middle sampling position. Samples were taken at two different depths at each position, one at approximately 20–25 cm below the ground surface and one 50–55 cm below the ground surface. At the sites used as arable land, the uppermost sample was taken above the level affected by ploughing, whereas the lowermost sample was taken at a depth which was assumed to be more or less unaffected by soil forming processes (i.e., the soil parent material).

The samples from arable land were taken in spade-dug holes (Figure 2-2) or with an Edelman corer (Figure 2-3). The samples in the wetlands were taken with a Russian peat corer (Figure 2-4) or with an Edelman corer. The five samples from each depth at each site were mixed together to form one bulk sample, giving two composite samples from each site representing the two sampled depths.

Figure 2-2. *One of the pits at AFM001374 where samples of glacial clay were taken. The red line represents the depth affected by ploughing. The clay below that level is characterised by light and dark layers representing the annual sedimentation during the latest deglaciation.*

Figure 2-3. *The Edelman corer was used for taking samples from some of the sites used as arable land.*

Figure 2-4. *The Russian peat corer used for sampling of peat from the five wetland sites. One meter long peat samples can be obtained with this corer.*

The size of the bulk samples was at least 1,750 mL for the clay and till samples. The corresponding size of the bulk peat samples was 1,000 mL. Each sample was divided into 4 sub-samples and sent to the laboratories for analysis. One sub-sample (250 mL) was sent to ALS Scandinavia AB laboratory in Luleå for elemental analysis, one sub-sample was sent to the Swedish University of Agricultural Sciences, SLU, in Uppsala for analysis of chemical soil properties, one sub-sample was sent to SLU for analysis of physical soil properties and one sub-sample was kept in the SKB archive for future use.

In addition to this, a steel cylinder was used to take samples with known volume. Two cylinder samples from each of the two sampling levels were taken from each sampled site (i.e., four cylinder samples were obtained from each site). It was not possible to sample peat from the wetlands with the steel cylinders due to the high content of water. Furthermore it was not possible to sample the lowermost level at one of the cultivated peat sites (AFM001382) with the cylinders due to high water content. The water contents and dry bulk densities of the samples taken with the steel cylinders were determined in the laboratory of Swedish Geology Survey, SGU, after drying the samples in the steel cylinders at 105°C. The water content corresponds to the content of water in the fresh samples.

2.1.2 Sampling of sandy till in deep trenches

In order to retrieve regolith samples from larger depth, two machine dug trenches within the Forsmark area were utilized yielding till samples from different depths (Table 2-1, Figure 2-1, Figure 2-5, Figure 2-6 and Figure 2-7). The trenches were dug the day before the sampling. The temperature overnight was almost –20°C, with the result that the regolith was frozen during sampling. This helped preserve the redox chemistry of the samples but made it difficult to obtain samples from a specific level large enough for analysis. In addition, the till in the trenches had a high water content, which in combination with the high silt content had caused flows of soil material along the walls of the trenches. The samples may therefore be contaminated by material from overlying regolith layers. However, in Trench 1 one sample (PFM007694) was taken from a fresh unfrozen wall, which eliminated the risk of contamination from overlaying layers.

Samples were taken from different levels in order to obtain samples that were affected and unaffected by soil forming processes. Six samples were taken from Trench 2 at 4 different positions (PFM007690, PFM007691, PFM007692 and PFM007693, see sketch in Figure 2-5) and 2 samples were taken in Trench 1 at one position (PFM007694). The samples were taken at specific depths below the ground surface, although the exact depths are somewhat uncertain since it was difficult to determine the exact level of the former ground surface. The samples are listed in Table 2-1.
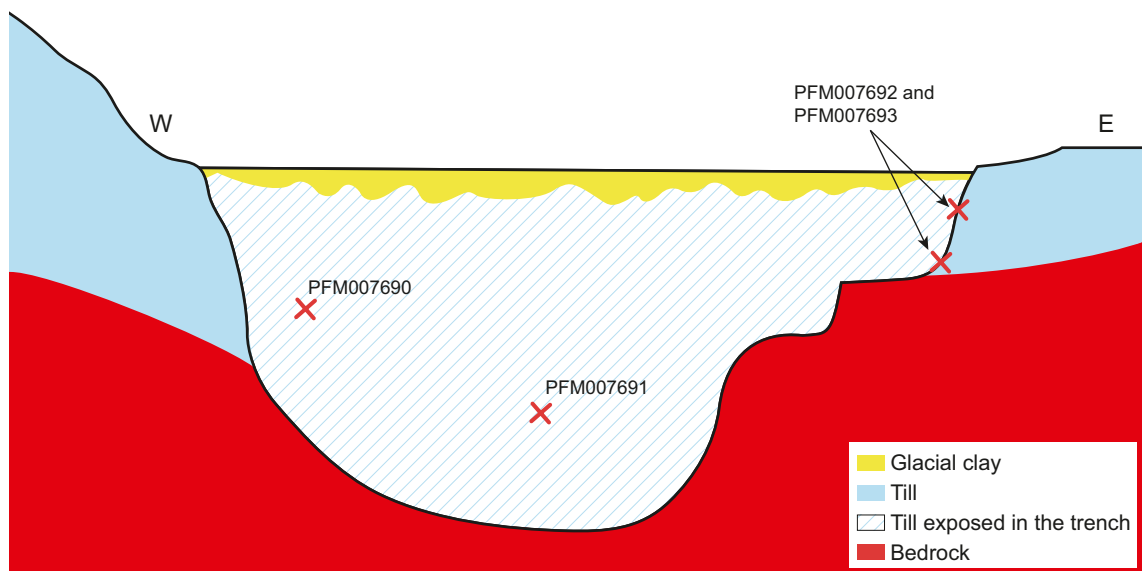
Figure 2-5. *Sketch of one of the two machine dug trenches (Trench 2) and the positions of the collected till samples. The sampled sites PFM007692 and PFM007693 were located very close, with a distance of a few meters in north-south direction. Two samples (at different depths) were taken on each of these two sites.*

Till was the dominating regolith type in Trench 2 (Figure 2-6). The till was partly overlain by a few decimetres of glacial clay (Figure 2-7). Trench 2 was situated close to a small pond where earlier stratigraphical studies were carried out (Sohlenius and Hedenström 2008). The till in that pond was also overlain by glacial clay, but also by a thin layer of postglacial sand. Trench 1 was totally dominated by till.

2.1.3 Sampling of marine sediment

Sampling of marine sediments was done at the coast of Forsmark in August 2010. The methods for sampling and analyses of surface sediment are described in /Engdahl et al. 2008/ and in one document published by the Swedish Environmental Protection Agency (Naturvårdsverket 2005).

Figure 2-6. *Trench 2 seen from the west towards the eastern side. The thickest layers of till were situated in the central part of the trench.*

Figure 2-7. *The till in Trench 2 was partly overlain by a few decimetres of glacial clay.*

Sediment samples were collected at one site, in the bay Kallrigafjärden (PFM006045, Figure 2-1). Sampling positions were recorded by a geographic positioning system (GPS), with an average accuracy of ± 0.5–1.0 m. Water depth was measured using an echo sounder with an accuracy of ± 0.05 m. A total of three sediment cores were taken using 60-cm-long metal-free polycarbonate tubes. Cores were accepted that provided intact sediment at least 35-40 cm in length. The samples were collected by a SCUBA diver. Between corings, the sampler, sediment slicer, and tubes were washed in detergent and rinsed before use.

Each core was described and two digital photos were taken of each core (Figure 2-8 and Figure 2-9). The sediment cores were then sliced and two layers, the surface layer 0-5 cm and a layer below the redox-front (or at approximately 25–35 cm depth if a redox front was not detected) were retained for analysis. Note that only two samples of the lower depth were retained, so that in total there were 5 samples. Each sample of a sediment layer was transferred to a separate, labelled, gas impermeable plastic bag and entrapped headspace air was removed by squeezing the bag. The plastic bags were then placed in labelled HDPE bottles filled with argon gas, two samples in each bottle, and chilled for transport to the analysis laboratory (ALS Scandinavia AB, in Luleå). The argon in the bottles was topped up periodically as new sample bags were placed in the bottles. The three samples from the upper level were combined into one bulk sample and then divided into two separate subsamples for analysis. The two samples from the lower level were also mixed into a bulk sample at the laboratory and then divided into two subsamples. These resulted in four samples, two from the upper level and two from the lower lever, see Table 2-1.

Figure 2-8. *One of the sampled sediment cores at site PFM006045.*

Figure 2-9. *One of the sampled sediment cores, the redox front is indicated by the field crew.*

2.1.4 Sampling of crops

Five vegetation (cereal) samples were collected from four of the sampling sites. The samples were taken before the regolith sampling at the same locations, and in each case five samples were taken and pooled together into a single composite sample per site. The sample area was 50 cm · 50 cm for each sample giving a total sampling area of 1.25 m² per site. From all 4 sites, grain, stems and roots of barley (*Hordeum vulgare*) were sampled, and similar samples of wheat (*Triticum aestivum*) were sampled from one of the sites (AFM001372). In Table 2-2, the sample numbers, regolith type and crop type are listed. Wheat grain is most often reserved for human consumption, but is fed to animals on occasion. Barley grain is most often used as animal feed or for brewery. Straw from both is not often used as animal feed, but it is possible, especially for beef cattle. In early crop stages, both grain and stems of cereals can be harvested green for animal feed.

2.2 Methods for analysis

Following sample collection, 50 regolith samples (30 mineral soils and 20 peats), 8 sandy till samples, 2 marine sediment samples and 5 crop samples were sent to the ALS Scandinavia AB laboratory in Luleå for elemental analysis. Regolith samples (excluding the marine sediments) samples were also sent to SLU in Uppsala for analysis of soil properties.

2.2.1 Incubation and extraction of pore water

For the regolith samples, dry matter content at 105°C and loss on ignition (LOI) at 550°C were determined on aliquots of the samples. Other aliquots were incubated in preparation for the extraction of pore water. These aliquots were not dried prior to extraction of pore water, but it was necessary to add extra water and incubate the moist regolith in order to extract enough pore water. Incubation involved filling two 50-mL syringes with weighed sample amounts and then adding high-purity, Milli-Q water. Water was added slowly to each syringe until the first drop fell from the syringe tip.

This moisture content is an operational field-capacity moisture content. It is somewhat wetter than field capacity would be in the field, but the incubated soil does retain air-filled pore space: it is not water-saturated. Each wetted sample was weighed and immediately transferred to a 50-mL, screw-capped, polypropylene centrifuge tube. Both duplicate syringes were then incubated for one week at room temperature. The mass of incubated material and the mass of Milli-Q water added to each syringe was recorded.

Several of the regolith samples were clays and clay-rich materials. Owing to the low permeability of these samples it was impossible to wet them with Milli-Q water in syringes as described above. Instead, these samples were placed in plastic beakers and Milli-Q water was added until the point of saturation, as judged by purely visual inspection. Afterwards, each sample was distributed between two 50-mL, screw-capped, polypropylene centrifuge tubes, and incubated as for the other samples. Separate dry matter content measurements were made at 105°C on incubated material for these 17 samples. The sample numbers were as shown in Table 2-1, modified with 'A' or 'B' to indicate the 20–25-cm depth or 50–55-cm depth, respectively. After incubation, the samples were directly centrifuged at 5,000 rpm for 15 min.

The marine sediment samples were shipped to the laboratory in argon-filled, sealed bags. These bags were opened in argon-filled, inflatable glove-boxes, and the samples within each layer (0–5 cm and 25–35 cm) were mixed together to get a composite sample from each level, resulting in two samples for analysis. The two samples were transferred to 50-mL, screw-capped, polypropylene centrifuge tubes. These samples already contained excess water and therefore there was no need to further incubate these materials, instead they were immediately centrifuged at 5,000 rpm for 15 min. The volume of pore water recovered from each sediment sample is reported.

2.2.2 Elemental analysis of pore water

Following centrifugation, the extracted pore water was collected in a syringe and aspirated through a 0.45-µm filter. One aliquot was acidified using HNO_3 (in-house, de-ionized) to pH < 2 before the determination of 69 elements by inductively coupled plasma sector field mass spectroscopy (ICP-SFMS). A second aliquot was taken directly (unacidified) for the quantification of Cl, Br and I by ICP-SFMS. Methane addition to the plasma was used in order to attain the best possible limits of quantification (LOQ) for Ag and Pd when using ICP-SFMS.

Separate determination of ^{226}Ra was carried out. The remaining volume of pore water (after the elemental analysis) was evaporated to dryness in acid-washed Teflon backers. The solid residue was digested with 5 mL of concentrated HNO_3 and the digest was evaporated to dryness. A droplet of 9M HCl was applied to a spot of the dried solid residue and Milli-Q water was added to provide an HCl of concentration 0.05M HCl. Radium was separated from solutions thus obtained using a cation exchange resin (AG 50W-X8, 100–200 mesh) following a procedure described elsewhere (Park et al. 1999). Purified fractions were analysed directly by ICP-SFMS. Recovery of ^{226}Ra was tested using CRM IAEA-428 and CRM IAEA-430 and was found to be in the 92–97% range (three separations per CRM). Unfortunately, insufficient pore water was recovered from two of the incubated samples (AFM001371A and AFM001371B) to allow ^{226}Ra to be determined.

2.2.3 Elemental analysis of solids

The solid material remaining after recovery of pore water was transferred to a plastic container for drying at 50°C. The dry matter content at 50°C was recorded. The dried samples were homogenized by grinding with an agate mortal and pestle. Aliquots were taken to measure dry matter content at 105°C and LOI at 550°C according to Swedish standard SS 028113-1. Elemental concentrations determined on material dried at 50°C were re-calculated and expressed on the basis of dry matter content at 105°C. Analytical background concentrations were also subtracted.

Solid samples were analyzed following digestion according to a method proposed by Activation Laboratories Ltd, involving *aqua regia* leaching of 0.5 g solid for 2 h in a heating block held at 90°C. Leachates were diluted and analyzed for 69 elements by ICP-SFMS with methane addition to achieve the best possible LOQs for Ag and Pd.

A separate preparation method was applied to samples prior to the determination of Cl, Br and I. This involved mixing the samples with ZnO + Na_2CO_3 and sintering at 550°C, extraction of Na halides with Milli-Q water, and batch purification using a cation exchanger. Analysis of the extract was then performed by ICP-SFMS. The method will recover halogens present in organic materials and soluble salts, but those bound in refractory minerals may not be detected with this method.

Separate analyses for [226]Ra were carried out, using 5 mL of *aqua regia* digest that was evaporated to dryness in acid-washed Teflon backers. These samples were subjected to the same AG 50W-X8 separation procedure as for pore waters. Because Ba, rare earth elements (REE) and Sr co-elute with Ra, further purification using an additional two columns (Ln resin and Sr*Spec resin) was applied following the procedure described by Larivière et al. (2003). Purified fractions were evaporated to dryness and residue was dissolved in 1.4 M HNO_3 followed by ICP-SFMS analysis. Note that as a quality assurance step, three laboratories did analysis of 3 samples during a pre-study. The results are further described in Appendix D. The results for the solid phase were considered in acceptable agreement with each other.

The marine sediment samples were analysed using two different extraction methods in order to investigate the effect of these methods on the results. One of the sub-samples was analysed in the same way as the regolith samples described above using *aqua regia* digestion. The other sub-sample was analysed after total digestion using two separate digestion methods according to Engdahl et al. (2008). The first method used was $LiBO_2$ fusion, where a mixture of sediment and $LiBO_2$ was fused in a carbon crucible at 1,000°C. The pearl formed on cooling was then dissolved in dilute acid. The second method was a microwave-assisted digestion in closed Teflon vessels using a nitric/hydrochloric/hydrofluoric acid mixture. The digestion method used before the analysis for total concentrations of 69 elements is listed here:

1. Analysis after $LiBO_2$ fusion: Al, Ca, Fe, K, Mg, Mn, Na, P, Si, Ti, Cr, Ga, Ge, Hf, Nb, Rb, Sc, Sr, Ta, Th, U, V, W, Y, Zr, Ce, La, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu.

2. Analysis after digestion using an acid mixture (HNO_3/HCl/HF) in sealed Teflon containers in a microwave oven: Ag, As, Au, B, Ba, Be, Bi, Cd, Co, Cs, Cu, Hg, Ir, Li, Mo, Ni, Os, Pb, Pd, Pt, Re, Rh, Ru, S, Sb, Se, Sn, Te, Tl and Zn.

The technique selected for the determination of each element depended on the concentration present in the analyzed sample. High concentrations are normally measured with ICP-AES (ICP Atomic Emission Spectroscopy) and lower levels (trace elements) with ICP-SFMS. Generally, the following applied:

ICP-AES: Al, Ca, Fe, K, Mg, Mn, Na, P, Si, Ti and S.

ICP-SFMS: Ag, As, Au, B, Ba, Be, Bi, Br, Cd, Cl, Co, Cr, Cs, Cu, Ga, Ge, Hf, Hg, I, Ir, Li, Mo, Nb, Ni, Os, Pb, Pd, Pt, Rb, Re, Rh, Ru, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Tl, U, V, W, Y, Zn, Zr, Ce, La, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu.

Note that all reported results for these samples had the blank subtracted and are expressed on a dry matter content (105°C) basis.

2.2.4   Elemental analysis of crops

The crop samples were divided into seeds, steam and root samples and they were washed or rinsed thoroughly with Milli-Q water in order to remove soil and dust particles. Washed samples were left to air dry in an environment protected from contamination for one week. After this the air-dried samples were homogenized and crushed, and the samples were oven-dried 50°C and weighed. Separate aliquots were dried at 105°C to obtain dry matter content, according to Swedish standard SS 028113-1. Elemental concentrations determined on material dried at 50°C were re-calculated and expressed on a dry-matter content (105°C) basis. Analytical background concentrations were subtracted.

Analysis of plant material was carried out for 69 elements with ICP-AES/ICP-SFMS after digestion with HNO_3/HF (trace) in sealed Teflon containers in a microwave oven. A separate preparation method was applied to samples prior to the determination of Cl, Br and I. This involved mixing the samples with ZnO + Na_2CO_3 and sintering at 550°C, extraction of Na halides with Milli-Q water, and batch purification using a cation exchanger. Analysis of the extract was then performed by ICP-SFMS.

Separate sub-samples were also sent to a sub-contractor for the determination of C and N. These analyses were carried out according to CEN/TS 15104:2007 by BELAB – Bränsle & Energilaboratoriet AB, Norrköping.

2.2.5 Analysis of physical and chemical properties

Sub-samples of soils and till were also sent to SLU in Uppsala for analysis of physical and chemical properties, specifically organic carbon content and particle grain size distribution including clay content (the method described by Ljung (1987) and the ICP Forests manual (ICP Forests 2010)). The samples were dried for 3–5 days and then crushed with a rubber hammer. Dry sieving was used to separate the fractions smaller and larger than 2 mm, and these fractions were weighed. For texture analysis, a sub-sample of the < 2 mm fraction was moistened with a little water and acidified by 1M HCl. Organic matter was oxidized by hydrogen peroxide (H_2O_2, 30%) in a boiling water bath. After oxidation, sodium hexametaphosphate (($NaPO_3$)$_6$, 3.3%) and sodium carbonate (Na_2CO_3, 0.7%) was used to disperse the soil and the sample was put in a 1-L sedimentation cylinder. The suspension was agitated overnight (12 hours), the sand fraction was separated by wet sieving, and the pH of the suspension was adjusted to 8. The sample was agitated again and then left still for sedimentation. The particle sizes were sampled by pipette at specific times and the weights of the particle fractions were determined after drying. Calcium carbonate in soils could occur either as discrete particles of calcite or as a cementing agent. In the latter case, the calcium carbonate should be removed by treatment with 2% hydrochloric acid. However, when calcite particles are present this treatment should be avoided, and this was the case for the Forsmark soil and till samples. Thus, carbonates were not dissolved prior to particle size analysis. The LOI, as a measure of organic matter content, was determined on a 10-g sample dried at 105 °C and then ignited at 550 °C for 3 hours.

For further chemical analyses (Karltun 1996), the samples were air-dried for 0.5-2 months. After this they were crushed with a wooden hammer and soil crusher and aliquots that passed a 2-mm sieved were used in the analysis. Determination of pH was made in H_2O and 0.01 M $CaCl_2$ and recorded after stabilization (0.3 to 1 minutes). Total carbon and nitrogen were determined by dry combustion in a LECO CNS 1000 instrument. Base cations Mn, Mg, Ca, Na and K were extracted in a 1M NH_4Ac (ammonium acetate) solution at pH 7 and Al in a I M KCl solution, and the concentrations extracted were measured by ICP-AES and expressed as cmol(+)/kg. Acidity was measured on the NH_4Ac solution by titration to pH 7 with NaOH. Cation exchange capacity (CEC) was calculated as the sum of base cations and acidity, so this was not an 'effective' CEC that should be calculated from base cations and Al. The calcium carbonate content was determined by a volumetric method according to Passon (Talme and Almén 1975).

2.3 Method of computation and statistical analysis

The basic computation of K_d is the concentration retained on the regolith solids (C_s, mg kg^{-1} dry regolith or Bq kg^{-1} dry regolith) divided by the concentration in the contacting pore water (C_w, mg m^{-3} or Bq m^{-3}), giving K_d in units of m^3 kg^{-1} dry soil. For elements with relatively low K_d values, where the K_d is in the same order of magnitude as the soil moisture content (expressed in the same units of m^3 kg^{-1} dry soil or sediment), then it is important to account for the amount of pore water dried onto the soil solids when the solids are prepared for chemical analysis. For elements with high K_d, this correction has little effect, but is still valid. Thus, the full equation was:

$$K_d = C_s/C_w - MC$$

where MC is the soil moisture content of the soil when dried for analysis in the same units as K_d (volume per mass dry soil). The correction for moisture content was only relevant and used for Cl.

Once K_d was computed for every (detectable) element in every sample, the log10 of the values were computed, and all statistical analyses were of log-transformed data. Where either C_s or C_w was missing, the K_d was considered a missing value and no attempt was made to replace the missing value with an estimate. As a result, there are fewer K_d values than numbers of samples for some elements. The summary statistics are numbers of K_d values, geometric mean (GM) and geometric standard deviation (GSD) which is presented in Appendix A.

Statistical analyses used log-transformed K_d and included Pearson correlations and analysis of variance (ANOVA). After inspection of the K_d results, it became evident that one of the 5 locations for the clay gyttja (AFM001363) yielded soils with pH > 7, whereas the other 4 had acidic pH. In retrospect, this soil was redefined as glacial clay (Sohlenius, personal communication). Additionally, it was very apparent that sampling depth was not a simple factor, and had different consequences in terms of soil chemistry from one regolith type to another. In the glacial clay both clay content and pH varied markedly with depth whereas they did not vary with depth in the other regoliths. Thus, the statistical model used in ANOVA was 'regolith type' with 5 degrees of freedom (df) and 'depth nested within regolith type' with 6 df, leaving 38 df for error (fewer df for error where data were missing). Within ANOVA, multiple means comparisons were by single degree of freedom contrasts evaluated with Scheffe's F test. Scheffe's F test is appropriate for *a posteriori* comparisons. Stastix 9.0 was used.

3 Results

3.1 Properties of regolith samples

In this section the sampled regoliths are described and the results from the analysis of chemical and physical properties are presented. The dry bulk density, LOI, pH in water, content of clay < 2 μm diameter (as fraction of total mineral content including gravel), CEC, total S and the K_d for Mn are shown in Table 3-1. The K_d for Mn and Fe can be used as *a posteriori* indicators of redox as both elements are markedly more soluble in reducing environments (Sheppard and Evenden 1985, Sheppard et al. 1990). More data, including pH in KCl, pH in $CaCl_2$, exchangeable cations, exchangeable acidity, total C content, organic C content, total N content and particle size (analysis into 8 size categories) are given in Appendix B.

All the soil properties in Table 3-1 varied significantly among the regolith types ($P < 0.05$), and the effect of depth within regolith type were significant for pH in water, clay content and the K_d for Mn. Table 3-2 shows that the deposits that were rich in organic material (clay gyttja and both peats) had considerably lower densities compared to the clay till and glacial clay, which were dominated by mineral materials. In Figure 3-1 a three dimensional representation of the soil properties illustrate that the peat soils had high CEC and LOI, while the glacial clay and clay till had low CEC and LOI. The pH was high for the clay till and for the deep samples of glacial clay while the shallow glacial clay samples had lower pH. The pH was also low for the peat samples and for the gyttja clay samples.

In general the sandy till samples from the machine-dug trenches were quite uniform, with the expected exception of higher organic matter content (greater LOI) for the shallow samples (30 and 50 cm). These shallow samples of sandy till also had slightly lower pH, the result of soil forming processes. Compared to the clay till samples from agricultural land (Table 3-2), these sandy tills had lower LOI, higher pH, and very low clay contents.

For the marine sediments there was insufficient sample to measure chemical and physical characteristics. The upper sediment had 5.9% LOI, and the lower anoxic sediment had 7.5% LOI, so both were essentially mineral materials. The total S was 0.7%, and sulphides might be expected to be present. The K_d for Mn was low and not different for the two sediment layers, suggesting that both may have been anoxic.

Table 3-1. Properties for each of the regolith samples. Note that texture analysis including clay content was not measured for the peat samples where the mineral fraction was < 30% by weight.

Sample number	Sampled depth (cm)	Regolith type	Dry bulk density (g cm⁻³)	Loss on ignition (%)	pH in H₂O	Clay < 2 μm (%)	CEC (cmol(+) kg⁻¹)	Total S (%)	K_d for Mn (m³ kg⁻¹)
AFM001356	20–25	Clay till	1.94	4.7	8.3	17	19	0.04	6.2
AFM001356	50–55	Clay till	1.99	1.9	8.4	32	19	0.10	340
AFM001357	20–25	Clay till	1.76	3.8	7.9	19	19	0.029	30
AFM001357	50–55	Clay till	1.93	1.5	8.4	24	17	0.012	87
AFM001359	20–25	Clay till	1.46	4.3	7.9	14	19	0.060	36
AFM001359	50–55	Clay till	1.72	1.6	8.3	16	16	0.042	410
AFM001361	20–25	Clay till	1.65	4.5	7.5	14	15	0.020	39
AFM001361	50–55	Clay till	1.73	1.6	8.0	15	16	0.009	460
AFM001362	20–25	Clay gyttja	0.89	18.7	5.1	10	19	0.23	0.09
AFM001362	50–55	Clay gyttja	0.55	15.8	4.6	50	19	0.37	0.16
AFM001363	20–25	Glacial clay[1]	0.78	18.0	7.3	26	25	0.19	0.64
AFM001363	50–55	Glacial clay[1]	1.17	3.2	8.0	59	24	0.11	530
AFM001365	20–25	Clay gyttja	0.70	24.5	4.9	56	33	0.33	0.74
AFM001365	50–55	Clay gyttja	0.56	13.9	4.0	48	23	0.35	0.70
AFM001367	20–25	Clay gyttja	0.78	17.5	5.2	53	26	0.18	0.33
AFM001367	50–55	Clay gyttja	0.58	11.2	4.4	53	22	0.26	0.39
AFM001368	20–25	Clay gyttja	0.72	16.6	5.2	50	26	0.19	0.11
AFM001368	50–55	Clay gyttja	0.55	11.5	5.1	52	9	0.26	0.15

Sample number	Sampled depth (cm)	Regolith type	Dry bulk density (g cm^{-3})	Loss on ignition (%)	pH in H$_2$O	Clay < 2 µm (%)	CEC (cmol(+) kg^{-1})	Total S (%)	K$_d$ for Mn (m^3 kg^{-1})
AFM001369	20–25	Glacial clay	0.80	20.6	6.9	35	41	0.21	0.83
AFM001369	50–55	Glacial clay	1.49	2.8	8.4	55	20	0.012	130
AFM001371	20–25	Glacial clay	1.59	4.1	6.1	41	16	0.021	2.4
AFM001371	50–55	Glacial clay	1.43	3.8	6.7	64	21	0.014	42
AFM001372	20–25	Glacial clay	0.89	9.4	6.7	24	18	0.087	1.9
AFM001372	50–55	Glacial clay	1.42	1.9	8.4	53	19	0.16	560
AFM001373	20–25	Glacial clay	1.78	4.5	7.9	34	22	0.025	150
AFM001373	50–55	Glacial clay	1.76	2.7	8.4	40	20	0.007	990
AFM001374	20–25	Glacial clay	1.33	9.6	7.3	51	33	0.082	1.6
AFM001374	50–55	Glacial clay	1.45	3.3	8.2	63	25	0.008	380
AFM001376	20–25	Clay till	1.65	5.0	7.9	16	22	0.031	190
AFM001376	50–55	Clay till	2.07	2.9	8.1	17	20	0.014	390
AFM001379	20–25	Cultivated peat	0.22	85.6	5.7		22	0.55	0.36
AFM001379	50–55	Cultivated peat	0.18	85.5	5.9		37	0.64	0.63
AFM001381	20–25	Cultivated peat	0.30	83.0	5.9		21	0.64	0.29
AFM001381	50–55	Cultivated peat	0.21	85.5	5.8		26	0.80	0.10
AFM001382	20–25	Cultivated peat	0.28	83.9	5.9		26	0.49	0.76
AFM001382	50–55	Cultivated peat		77.2	5.9		85	0.53	0.63
AFM001383	20–25	Cultivated peat	0.25	84.6	6.1		26	0.41	2.0
AFM001383	50–55	Cultivated peat	0.14	90.3	6.1		24	0.70	11
AFM001384	20–25	Cultivated peat	0.32	83.7	6.1		31	0.33	1.3
AFM001384	50–55	Cultivated peat	0.29	83.6	6.2		35	0.53	0.71
AFM001385	20–25	Wetland peat		95.7	4.3		120	0.31	0.49
AFM001385	50–55	Wetland peat		97.0	4.4		108	0.35	0.81
AFM001387	20–25	Wetland peat		88.3	5.6		161	1.0	0.81
AFM001387	50–55	Wetland peat		92.8	5.8		151	1.1	0.63
AFM001388	20–25	Wetland peat		92.7	6.4		120	0.62	0.36
AFM001388	50–55	Wetland peat		92.3	6.4		125	0.89	1.5
AFM001389	20–25	Wetland peat		94.5	6.2		101	0.81	0.24
AFM001389	50–55	Wetland peat		93.1	6.5		116	0.77	0.41
AFM001391	20–25	Wetland peat		92.3	5.9		136	0.62	0.49
AFM001391	50–55	Wetland peat		93.3	5.9		123	0.98	1.1
PFM007690_1	180	Sandy till		0.0048	9.23	2.4	10.5	0.18	0.40
PFM007691_1	350	Sandy till		0.0048	9.26	1.9	10.2	0.15	0.52
PFM007692_1	50	Sandy till		0.013	8.55	2.5	11.5	0.15	1.39
PFM007692_2	100	Sandy till		0.0059	9.19	2.1	10.6	0.12	3.41
PFM007693_1	30	Sandy till		0.015	8.53	3.7	12.7	0.17	0.20
PFM007693_2	100	Sandy till		0.0069	9.1	1.9	10.6	0.17	0.56
PFM007694_1	250	Sandy till		0.0049	9.02	2.2	9.8	0.17	0.72
PFM007694_2	250	Sandy till		0.0050	8.94	2.1	10.5	0.17	0.59

[1] this categorization was re-assigned after sampling.

Table 3-2. Average (standard deviation) of properties of the soil and peat samples by type of regolith, along with statistical interpretation, and the results for sandy till (the latter were not included in the statistical tests).

Regolith type (number of samples)	Dry bulk density (g cm^{-3})	Loss on ignition (%)	pH in H$_2$O	Clay < 2 μm (% of mineral fraction)	Cation exchange capacity (cmol(+) kg^{-1})	Total S (%)	K$_d$ for Mn (m^3 kg^{-1})
F test[1] of QD	***	***	***	***	***	***	***
F test[1] of depth within QD	ns	ns	*	*	ns	ns	***
Clay till (10)	1.8 (0.2)	3.4 (1.5)	8.1 (0.29)	17 (5.0)	18 (2.1)	0.036 (0.029)	100 (4.3)[2]
Clay gyttja (8)	0.67 (0.13)	16 (4.4)	4.8 (0.45)	46 (15)	22 (7.0)	0.27 (0.073)	0.25 (2.3)
Glacial clay (12)	1.3 (0.35)	6.5 (5.9)	7.0 (0.61)[3]	35 (9.9)[3]	24 (7.0)	0.10 (0.081)	2.9 (7.4)[3]
			8.0 (0.67)	56 (9.2)			290 (3.2)
Cultivated peat (10)	0.24 (0.06)	81 (6.5)	6.0 (0.16)	–	33 (19)	0.56 (0.14)	0.76 (3.5)
Wetland peat (10)	–	91 (3.6)	5.7 (0.78)	–	130 (19)	0.75 (0.27)	0.59 (1.7)
Sandy till (8)	–	0.008 (0.004)	9.0 (0.3)	2.4 (0.6)	11 (0.9)	0.018 (0.004)	0.68 (2.3)

[1] statistical inferences indicated by ns – not significant (P > 0.05), * – significant at P < 0.05, and *** – significant at P < 0.001.

[2] for K$_d$ the value in parentheses is the geometric standard deviation, K$_d$ is shown here as a possible indicator of redox effects.

[3] the data for the 22-cm and 52-cm depths are given separately for pH, clay content and K$_d$ for Mn in the glacial clay because the significant effect of depth within QD was because of this soil, the upper value is the 22-cm depth and lower is the 52-cm depth.
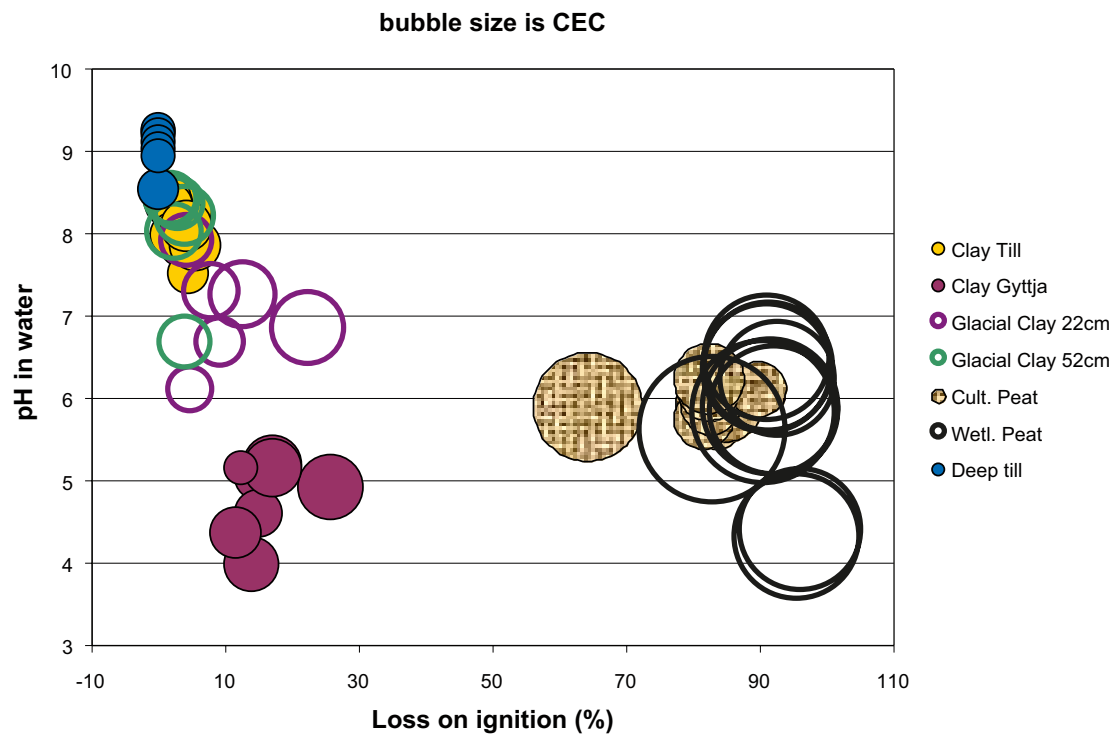
Figure 3-1. *Three dimensional representation of agricultural regolith, peat and sandy till (here called deep till) samples, where bubble size is proportional to cation exchange capacity. Note that the glacial clay samples differed by depth and so for this soil the depths are shown differently.*

3.1.1 Clay till

Five of the sampled sites were fields with regolith classified as clay till (AFM001356, AFM001357, AFM001359, AFM001361 and AFM001376), see Figure 3-2, Figure 3-3 and Figure 3-4. Clay till is common in north-eastern Uppland and in the Forsmark area. Clay tills contain between 5 and 15% clay. However, results from grain size analyses show that some of the samples analysed here had clay contents above 15% (Table B-3) and should consequently be classified as boulder clay. The term clay till is used for the sample discussed here since the sampled sites originally were chosen in areas classified as clay till on SGU's maps of Quaternary deposits. In the Forsmark area the clay till is partly used as agricultural land. The areas with the lowest frequency of surficial boulders were probably chosen for cultivation. Stones and coarser material has been taken away and can be seen in the heaps of rounded stones, which are common around areas with cultivated clay till in the Forsmark area (Hedenström and Sohlenius 2008).

Compared to the more commonly occurring forested sandy till, pH and CEC are relatively high in these cultivated clay till soils. The results presented here can be compared with the sandy till studied by SKB at the Laxemar sites, which are more normal in a Swedish context (Sohlenius and Hedenström 2008).

3.1.2 Sandy till

Five of the sampled sites were situated at locations with sandy silty till (PFM007690, PFM007691, PFM007692, PFM007693 and PFM007694), see Figure 3-5. All samples were taken in two machine-dug trenches. This till have not been used for agricultural purposes.

The till has a high pH compared to most other forested till soils in Sweden, e.g. at the Laxemar site (Sohlenius and Hedenström 2008). That is due to the occurrence of $CaCO_3$ in the Forsmark tills. The soils at the sampled sites were situated less than 2 m above the sea level and have consequently been subjected to chemical weathering for less than 500 years. These soils will become more acid in the future as the $CaCO_3$ is leached out from the uppermost soil horizons.

Figure 3-2. *Clay till at sampling site AFM001356.*

Figure 3-3. *The clay till at sampling site AFM001359. The clay till is characterised by the abundance of stones and gravel. The cylinder has a diameter of 5 cm, and was used for taking samples to calculate density and porosity.*

Figure 3-4. *The clay till at site AFM001359.*

Figure 3-5. *Sandy till at PFM007692, which was situated in a machine-dug trench.*

3.1.3 Clay gyttja

Five of the sampled sites were supposed to be situated at sites with clay gyttja (AFM001362, AFM001363, AFM001365, AFM001367 and AFM001368), see Figure 3-6 and Figure 3-7. The results from analyses of physical and chemical properties show, however, that the samples from AFM001363 represented a clay with a low organic content (Tables in Appendix B) and could not be classified as clay gyttja. The samples from AFM001363 had properties which were similar to the properties of glacial clay (see below). During sampling, the water draining from the soils at AFM001365, AFM001367 and AFM001368 were noted to be dark and especially rich in dissolved humic substances.

Studies of clay gyttja from sites around Lake Mälaren has shown that these materials often contains iron sulphides below the ground water table (Sohlenius and Öborn 2004). In areas with arable land the ground water table has been lowered and the sulphides have consequently oxidized. That has caused a lowering of pH and leaching of many elements (e.g. Y and Ni) due to increased chemical weathering. That may in turn explain the relatively low pH and high pore water concentrations of many elements in the clay gyttja soils studied here. The analysed gyttja clay samples are also relatively high in sulphur, which may be due to sulphate formed after oxidation of sulphide minerals. The oxidised clay gyttja soils are often characterised by precipitations of iron oxides, which also was observed in this study (Figure 3-6). The clay gyttja soils have relatively high concentrations of Cl and Br, which may be because these materials were deposited in brackish water.

Figure 3-6. *Clay gyttja sampled at site AFM001367. The clay gyttja was originally formed in an anoxic environment. The uppermost soil is now oxidised as a consequence of an artificial lowering of the ground- water table which was done to obtain arable land. The oxidising condition is visualised by the patches of rust (iron oxides), which can be seen on the photo.*

Figure 3-7. *One of the sites where clay gyttja was sampled (AFM001362). At all these sites the ground-water table has been lowered with ditches.*

3.1.4 Glacial clay

Five sites with glacial clay were sampled (AFM001369, AFM001371, AFM001372, AFM001373, AFM001374), see Figure 3-8 and Figure 3-9. As noted above, the samples from AFM001363 also represented glacial clay.

The glacial clay is low in organic carbon but contains some inorganic carbon, most probably emanating from $CaCO_3$ (Persson 1985). Also the lowermost sample from AFM001363 (originally classified as clay gyttja) contains some inorganic carbon ($CaCO_3$). Postglacial clays from the Forsmark area have similar properties as glacial clay (e.g. low content of organic carbon) but lack $CaCO_3$. That further suggests that the deposits at AFM001363 site should be classified as glacial clay. The occurrence of $CaCO_3$ explains the high pH in the samples representing glacial clay. The uppermost samples from above the plough layer have generally a lower clay content compared to underlying sediments.

Figure 3-8. *Glacial clay at site AFM001374. The varved glacial clay is visible in the lower part of the pit.*

Figure 3-9. *Cultivated glacial clay at the sampled site AFM001374.*

3.1.5 Cultivated peat

Five sites with cultivated peat were sampled (AFM001379, AFM001381, AFM001382, AFM001383 and AFM001384), see Figure 3-10 and Figure 3-11. These sites are all situated in former fens where the ground water table has been artificially lowered. That has caused oxidising conditions in the upper-most peat layers. The peat is almost entirely composed of organic material, which is reflected by high LOI values and low densities. The LOI values are however lower in the cultivated peat than in the wetland peat (see below). That may be due to enrichment of minerogenic material as a consequence of oxidation of organic material. The peat layers have most probably subsided as an effect of oxidation and compaction after the lowering of the groundwater table.

3.1.6 Wetland peat

Five sites with wetland peat were sampled (AFM001385, AFM001387, AFM001388, AFM001389 and AFM001391), see Figures 3-12 to 3-15. The ground water table was situated close to the surface in the wetlands. In contrast to the cultivated peat areas, reducing conditions may consequently occur close to the ground surface. During sampling, the soils at AFM001389 and AFM001391 had strong odours of H_2S, indicative of chemically reducing conditions. The LOI values were generally higher in the wetland peat than in the cultivated peat areas. The sampled wetlands had somewhat different vegetation, which also affects the properties of the peat that is built up by remnants from the vegetation. AFM001385 had a high proportion of Sphagnum species, reflecting the nutrient poor conditions at that site. That is further reflected by high LOI, low pH, high acidity and low concentrations of most analysed elements. The wetlands represented by AFM001387 and AFM001388 were dominated by sedge whereas AFM001389 and AFM1391 were dominated by reed. These sites are more nutrient rich than the wetland represented by AFM001385. Samples from these sites were also characterised by higher pH and lower acidity than the samples from AFM001385.

Figure 3-10. *Cultivated fen peat at the sampled site AFM001384.*

Figure 3-11. *Cultivated fen peat at site AFM001382. The ground water table is situated within a few decimetres from the ground surface. The cylinder has a diameter of 5 cm, and was used for taking samples to calculate density and porosity.*

Figure 3-12. *Peat sample form site AFM001385 (Stenrösmossen). The peat is dominated by Sphagnum species and has a low degree of humification.*

Figure 3-13. *The sampled site AFM001385 in the fen Stenrösmossen. The vegetation at the site indicates nutrient poor conditions.*

Figure 3-14. *The wetland at site AFM001387 is dominated by sedge.*

Figure 3-15. *The wetland at site AFM001389 is dominated by reed*.

3.2 K_d values

In this section the K_d values measured in the agricultural land, wetland, sandy till and marine sediments are presented and evaluated.

3.2.1 K_d for agricultural regoliths and wetlands

The K_d data for all elements measured in the wetlands and agricultural lands are shown in Table 3-3. For most elements, the K_d values differed among the regolith types, and for many of the elements the K_d varied with depth within the regolith (see columns 3 and 4 of Table 3-3). This significant interaction of depth and regolith means that simple averages of K_d by regolith, averaging samples from the two depths, could be misleading. Additionally, even averages by regolith for a given depth will vary not just because of parent material, but also because of pH: the clay till was basic at both depths, the clay gyttja was acidic at both depths, and the glacial clay varied in pH with depth.

Clearly, a strong determinant of K_d was pH, and among the clay soils there were significant differences between acidic and basic layers (column 5 of Table 3-3) for many of the elements. Using Al as an example, the K_d values in the acidic clay gyttja were nearly 2 orders of magnitude lower than in the basic clay till. This was also evident comparing within the glacial clay where the deep layers were basic and the K_d was markedly higher compared to the surface layers that were neutral pH. The general effect of acidic conditions in the clay soils was to lower K_d; none of the elements had K_d that was more than 7-fold higher in acidic conditions than basic, but many were more than tenfold lower in acidic conditions.

To further investigate the effect of pH, the K_d for acidic and basic soils are plotted in Figure 3-16 (upper plot). Each point is a different element, and basic regoliths generally had substantially higher K_d values than the acidic regoliths, especially when the basic K_d was > 10 m^3 kg^{-1}. Note that Mn is especially different between the acidic and basic categories. That the K_d values for acidic versus basic tend to diverge at higher K_d is quite important because K_d values > 10 m^3 kg^{-1} indicate strong retention and minimal mobility whereas < 10 m^3 kg^{-1} there is potential for migration. Thus the effect of pH on K_d is less important because it mostly applies to elements that are relatively immobile at either pH. These elements as contaminants from buried waste are less likely to reach the surface.

Differences between mineral and peat soils are expected – they have few common properties. Again, comparing among the acidic soils (there were no basic peat samples), the peat samples had significantly different K_d values than the acidic clay soils for many elements (column 6 of Table 7). Generally, the K_d was lower in the peat soils, and the K_d in peat soils was more than tenfold lower for Al, As, Cs, Fe, Ga, K, Li, Mn, Rb, Sc, Th, Ti, Tl and V (compared at the 22-cm depth). Only for Cd and U were the K_d values in the peat more than tenfold higher than in the mineral soils (compared at the 22-cm depth). It should also be remembered that the peat soils had dry bulk densities that were about 6-fold lower than the mineral soils. Thus, in terms of the ability of a landscape to retain an element, the peat soils are even less retentive. To express K_d on a volume-of-soil basis (unitless), the value in a peat soil would be ~6-fold lower than a mineral soil.

The lower plot in Figure 3-16 compares clay and peat soils. Elements such as Cl, I and S are expected to have higher K_d in organic soils because of incorporation into organic material created by photosynthesis in plants, and the K_d values for S in organic soils were higher than in mineral soils. Both Rb and Cs, and to a lesser extent the related element K, were distinctly different between acidic clay and organic soils (Figure 3-16, lower plot). These elements are noted for being retained within layers of clay minerals, resulting in especially high K_d values in clay soils. In Table 3-3, contrasts of the effect of depth within each QD are also shown, and in general these contrasts were significant most often between the depths of the glacial clay where the pH and clay content also varied with depth.

Table 3-3. Geometric means of K_d values (m^3kg^{-1}) by regolith type and depth. Note that sampling depth caused variation in soil chemistry that differed among the regolith.

	N[1]	Overall effect of QD[2]	Overall effect of depth within QD[2]	Among clay soils, acidic versus basic[3]	Among acidic soils, mineral versus organic[3]	Residual GSD[4]	Clay till (n=5)[1]		Clay gyttja (n=4)		Glacial clay (n=6)		Cultivated peat (n=5)		Wetland peat (n=5)	
Depth (cm)							22	52	22	52	22	52	22	52	22	52
LOI (%)[5]							4.5	2.2	19	13	10	2.9	83	81	91	92
Clay (% of total mineral)							16	19	42	50	35	56	–	–	–	–
pH in water							7.9	8.2	5.1	4.5	7.0	8.0	5.9	6.0	5.7	5.8
Total S (%)							0.035	0.036	0.23	0.31	0.68	0.81	0.48	0.64	0.68	0.81
Acidity class[6]							basic	basic	acidic	acidic	acidic	basic	acidic	acidic	acidic	acidic
Ag	49	***[7]	***			2.1	3.2	1.4	3.1	2.2	1.9	0.47*	3.0	2.7	12	2.5*
Al	50	***	**	***		3.0	420	280	4.8	6.1	29	590*	5.8	6.9	11	12
As	50	***	***		***	2.0	2.2	4.1	1.5	6.4	1.2	7.3*	0.70	0.22	0.35	0.27
Au	34					2.4	0.048	0.042	0.046	0.042	0.083	0.08	0.33	0.39	0.095	0.076
B	50	***		*	***	1.7	0.061	0.064	0.027	0.025	0.044	0.088	0.086	0.063	0.17	0.13
Ba	50	**	***			1.7	1.2	2.0	0.67	2.5	0.96	3.1*	0.97	0.85	0.83	1.10
Be	50	***	*	***		1.8	6.6	6.6	1.2	0.55	3.3	9.2*	1.6	1.7	0.50	0.63
Bi	50	***	***	**		2.3	96	59	4.8	33	7.6	130*	15	12	12	14
Br	50	***	***	*	***	1.6	0.06	0.04	0.06	0.20*	0.068	0.050	0.15	0.19	0.29	0.70
Ca	50	***	**	**	***	2.0	0.14	0.49	0.05	0.04	0.08	0.30*	0.25	0.24	0.31	0.38
Cd	34	***			***	3.0	10	2.1	0.33	0.07	2.0	1.7	12	66	13	32
Ce	50	***	***	***	*	2.1	130	99	3.0	1.7	8.2	130*	14	13	13	15
Cl	48	***				2.2	0.0043	0.052	0.012	0.011	0.0071	0.0046	0.033	0.043	0.020	0.036
Co	50	***	***	***		1.9	18	28	0.44	0.57	4.2	65*	1.4	1.6	1.7	2.7
Cr	50	***	*	***		2.4	72	110	3.8	8.9	11	61	4.6	4.1	3.5	5.5
Cs	50	***		*	***	2.7	500	420	24	36	97	370	4.7	4.2	0.46	0.47
Cu	50	***	***	*	***	1.7	1.4	1.5	0.77	1.39	0.98	3.3*	2.5	2.7	11	8.6
Dy	50	***	***	***	***	2.0	43	40	2.2	1.4	5.1	79*	11	10	9.3	13
Er	50	***	***	***	**	2.0	37	32	1.7	1.3	4.5	61*	10	8.2	7.4	10
Eu	30	***		***		2.7	–	74	2.6	1.5	6.6	92	11	9.1	4.1	13
F	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fe	50	***	***	***		2.8	330	210	3.9	17	14	670*	12	13	5.2	15
Ga	50	***	***	*		2.7	240	190	21	170	54	400*	6.8	6.8	11	10
Gd	50	***	***	***	**	2.1	49	51	2.6	1.6	6.0	96*	13	13	11	14
Ge	50					2.1	1.1	1.5	0.55	0.95	0.60	1.3	0.63	0.55	1.2	1.0
Hf	50	***	***	***		2.2	5.9	11	0.35	3.5*	0.95	50*	2.9	2.5	1.8	2.9

	N[1]	Overall effect of QD[2]	Overall effect of depth within QD[2]	Among clay soils, acidic versus basic[3]	Among acidic soils, mineral versus organic[3]	Residual GSD[4]	Clay till (n=5)[1]		Clay gyttja (n=4)		Glacial clay (n=6)		Cultivated peat (n=5)		Wetland peat (n=5)	
Depth (cm)							22	52	22	52	22	52	22	52	22	52
LOI (%)[5]							4.5	2.2	19	13	10	2.9	83	81	91	92
Clay (% of total mineral)							16	19	42	50	35	56	–	–	–	–
pH in water							7.9	8.2	5.1	4.5	7.0	8.0	5.9	6.0	5.7	5.8
Total S (%)							0.035	0.036	0.23	0.31	0.68	0.81	0.48	0.64	0.68	0.81
Acidity class[6]							basic	basic	acidic	acidic	acidic	basic	acidic	acidic	acidic	acidic
Hg	49	***				2.1	7.6	3.2	4.5	2.3	3.0	1.7	9.3	11	9.8	11
Ho	50	***	***	***	**	2.0	39	35	2.0	1.4	5.1	74*	11	10	9.6	13
I	50	*	***			2.0	0.30	0.19	0.09	0.66*	0.11	0.24	0.25	0.43	0.20	0.73
In	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ir	3	–	–	–	–	–	–	–	–	–	–	–	0.10	1.2	–	–
K	50	***			***	2.4	0.43	0.60	0.94	2.4	0.41	1.5	0.22	0.18	0.045	0.042
La	50	***	***	***	*	2.1	76	73	3.0	1.5	7.4	120*	14	13	13	15
Li	50	***			***	2.4	1.7	2.5	1.3	0.56	2.9	2.4	0.22	0.29	0.056	0.043
Lu	50	***	***	***	**	2.0	32	25	1.3	1.2	4.2	50*	8.5	8.1	6.8	9.5
Mg	50	***				2.1	1.2	2.4	0.72	0.95	0.65	2.0	0.15	0.19	0.16	0.19
Mn	50	***	***	***		3.2	35	290	0.22	0.29	2.9	140*	0.73	0.79	0.44	0.80
Mo	50	***				2.3	0.17	0.09	2.0	13	0.18	0.19	0.41	0.58	4.4	4.9
Na	50	***				1.7	0.044	0.053	0.016	0.021	0.020	0.040	0.0092	0.011	0.012	0.013
Nb	50	***	***	***		2.3	55	80	5.0	27	7.0	130*	3.6	4.5	7.3	12
Nd	50	***	***	***	*	2.1	58	66	2.6	1.6	6.4	99*	14	13	11	14
Ni	50	***	***	***	**	1.6	3.30	6.15	0.45	0.46	1.5	13*	1.67	1.96	1.93	2.62
Os	32					3.0	0.26	0.37	0.17		0.87	0.20	0.30	0.58	1.02	0.75
P	50					1.9	3.1	3.5	2.5	2.8	2.5	5.3	3.3	1.4	2.5	3.0
Pb	50	***	***	***		2.6	230	96	4.3	4.9	11	220*	18	20	18	20
Pd	4	–	–	–	–	–	4.6	–	0.64	–	–	–	–	–	–	4.8
Pr	50	***	***	***	*	2.1	67	72	2.7	1.6	6.8	110*	14	13	12	15
Pt	2	–	–	–	–	–	0.078	–	–	–	–	–	–	–	–	0.37
Ra-226	48	***				2.1	9.6	7.8	2.1	3.3	3.0	11	2.2	1.8	2.1	2.1
Rb	50	***		***		2.6	24	20	2.3	4.5	7.9	21	0.39	0.44	0.064	0.068
Re	49	***			***	2.5	0.12	0.041	0.016	0.069	0.068	0.067	0.30	0.38	0.41	0.68
Rh	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ru	25					4.3	0.57	3.2	0.75	0.56	1.2	3.1	0.93	0.38	3.6	0.40
S	50	***			***	2.1	0.043	0.044	0.033	0.044	0.033	0.016	0.10	0.094	0.94	0.54

	N[1]	Overall effect of QD[2]	Overall effect of depth within QD[2]	Among clay soils, acidic versus basic[3]	Among acidic soils, mineral versus organic[3]	Residual GSD[4]	Clay till (n=5)[1]		Clay gyttja (n=4)		Glacial clay (n=6)		Cultivated peat (n=5)		Wetland peat (n=5)	
Depth (cm)							22	52	22	52	22	52	22	52	22	52
LOI (%)[5]							4.5	2.2	19	13	10	2.9	83	81	91	92
Clay (% of total mineral)							16	19	42	50	35	56	–	–	–	–
pH in water							7.9	8.2	5.1	4.5	7.0	8.0	5.9	6.0	5.7	5.8
Total S (%)							0.035	0.036	0.23	0.31	0.68	0.81	0.48	0.64	0.68	0.81
Acidity class[6]							basic	basic	acidic	acidic	acidic	basic	acidic	acidic	acidic	acidic
Sb	50	***	**		*	1.5	0.42	0.39	0.59	1.1	0.54	1.2*	1.1	0.82	2.0	2.4
Sc	50	***	***	***		1.9	100	59	2.1	3.3	9.6	100*	4.9	4.0	2.0	2.3
Se	30					1.9	0.98	0.80	1.3	1.5	0.84	0.92	2.3	1.3	1.0	0.44
Si	50	***				2.1	0.37	0.53	0.47	0.37	0.15	0.22	0.11	0.064	0.15	0.17
Sm	50	***	***	***	*	2.1	54	60	2.5	1.6	6.0	96*	13	13	12	13
Sn	50					2.7	5.2	4.6	4.4	6.3	10	11	7.4	3.0	5.3	10
Sr	50	***	***	*	**	1.8	0.12	0.34	0.082	0.074	0.10	0.51*	0.28	0.26	0.32	0.39
Ta	48		***	**		3.0	2.53	4.3	0.30	2.32	0.34	7.5*	3.0	2.2	2.2	2.3
Tb	50	***	***	***	**	2.1	50	47	2.4	1.5	5.6	98*	13	12	10	14
Te	50	*	*			2.7	1.9	2.2	1.5	2.2	1.7	11*	1.3	1.6	1.1	1.3
Th	50	***	***	***		2.2	77	67	2.6	9.5	6.1	91*	7.1	5.4	2.6	2.0
Ti	50	***	***	***		2.8	250	320	11	110	26	470*	9.6	14	18	15
Tl	50	***				2.6	24	18	2.6	3.4	9.4	37	0.71	0.83	1.4	1.1
Tm	50	***	***	***	*	2.1	36	31	1.6	1.3	4.6	62*	9.1	8.7	8.4	10
U	50	***			**	2.5	0.37	0.34	3.0	3.4	0.47	0.45	15	15	9.9	19
V	50	***	***	**		2.3	10	25	3.6	62*	7.0	100*	2.8	3.4	6.2	9.2
W	48		***			2.4	6.4	8.5	3.6	17	3.6	17*	4.3	3.4	5.1	2.0
Y	50	***	***	***	**	1.9	33	27	1.5	0.97	4.4	58*	8.8	7.9	7.7	10
Yb	50	***	***	***	**	2.0	35	29	1.4	1.2	4.4	59*	8.8	8.5	7.1	10
Zn	50	***		*		1.9	5.6	5.2	0.90	0.64	6.0	15	1.3	1.1	3.3	2.7
Zr	50	***	***	***	*	2.0	3.6	7.3	0.35	2.6*	0.88	34*	2.7	2.1	2.4	3.3

[1] N is number of samples with detectable K_d values, n is the number of samples of this regolith type that were sampled.

[2] These are the results of the overall F tests by analysis of variance of the model: regolith type and depth nested within regolith type.

[3] These are *a posteriori* single degree of freedom contrasts, evaluated by Scheffe's F test.

[4] Residual geometric standard deviation computed from the residual (unexplained or random) error after analysis of variance.

[5] Loss on ignition, indicative of organic matter content.

[6] Soils with average pH less than or equal to 7.0 were classified here as acidic.

[7] Statistical inferences indicated by * – significant at $P < 0.05$, ** – significant at $P < 0.01$, *** – significant at $P < 0.001$. otherwise – not significant ($P > 0.05$),
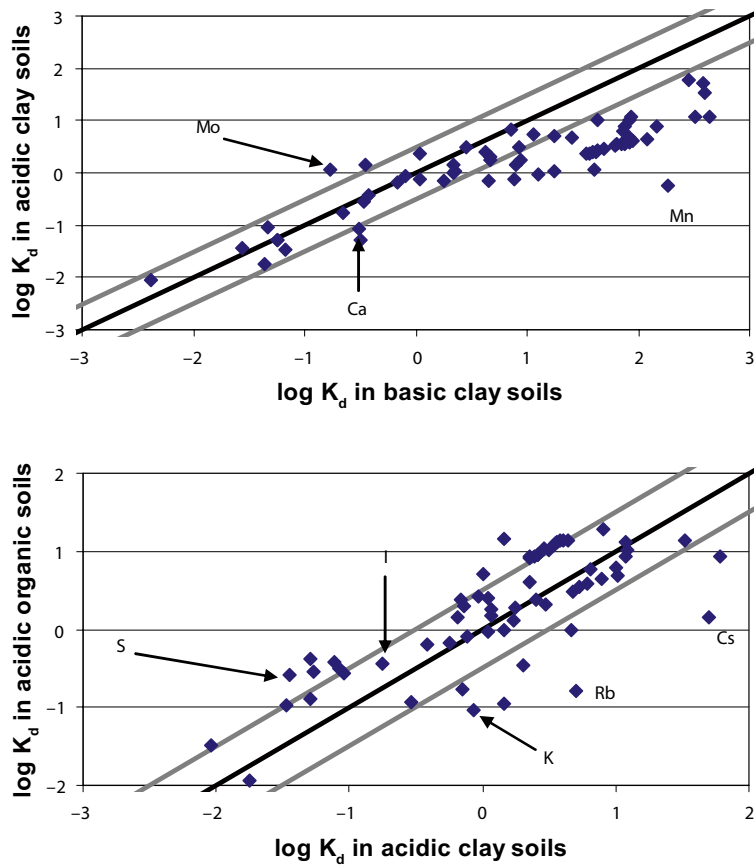
Figure 3-16. *Comparison of log K_d between the acidic and basic regolith groups. The black line is the 1:1 correspondence and the grey lines are approximately 1 GSD above and below this. Each point is a different element.*

3.2.2 K_d for sandy till samples

The K_d values for the 8 sandy till materials are shown in Table 3-4, and their relationship to the K_d for agricultural soils and wetlands in Table 3-3 are shown in Figure 3-17. Based on the pH of the till samples, they are most like the clay till soil, as shown in the right-hand plot in Figure 3-17. Not surprisingly, the K_d is higher in the clay till soil than in the sandy till samples collected in the deep trenches, the sandy till had very low clay and organic matter contents.

There were too few samples to thoroughly consider the effect of depth among the sandy till samples, but there were significant negative correlations between log K_d and depth for Ba, Cs, Ga, Rb, Sb, Se and ^{226}Ra. For these elements, the K_d was lower for the deeper samples. The deeper samples also had slightly lower LOI and clay contents and slightly higher pH.

Table 3-4. Sandy till K_d values (m^3 kg^{-1}).

Element	GM	GSD	Element	GM	GSD	Element	GM	GSD
Ag	0.80	3.5	Hf	6.4	3.9	Ru	0.40	2.1
Al	261	2.5	Hg	2.3	2.1	S	0.024	1.7
As	0.40	1.6	Ho	5.0	1.6	Sb	0.039	3.0
Au	0.019	1.3	I	0.013	1.9	Sc	8.0	1.6
B	0.0068	3.8	K	0.036	2.1	Se	0.11	3.0
Ba	0.19	2.0	La	8.9	1.8	Si	0.20	1.3
Be	6.6	1.5	Li	0.30	1.9	Sm	9.3	1.8
Bi	14	3.3	Lu	3.1	1.5	Sn	11	1.5
Br	0.0050	2.7	Mg	0.10	2.0	Sr	0.11	1.7
Ca	0.28	1.5	Mn	0.68	2.3	Ta	1.4	1.8
Cd	1.1	8.3	Mo	0.014	3.9	Tb	6.8	1.6

Element	GM	GSD	Element	GM	GSD	Element	GM	GSD
Ce	9.6	1.8	Na	0.0013	3.4	Te	1.3	2.6
Cl	0.00076	4.0	Nb	27	2.3	Th	21	2.3
Co	2.5	2.2	Nd	9.2	1.8	Ti	833	4.9
Cr	49	2.9	Ni	0.75	1.4	Tl	0.64	3.1
Cs	11	2.2	Os	0.62	4.8	Tm	3.9	1.5
Cu	0.44	1.4	P	14	1.9	U	0.017	3.6
Dy	6.0	1.6	Pb	16	1.7	V	7.1	2.1
Er	4.3	1.6	Pr	9.8	1.8	W	1.9	2.4
Eu	7.8	1.8	Pt	0.070	2.0	Y	4.1	1.6
Fe	142	3.0	^{226}Ra	1.3	2.3	Yb	3.6	1.5
Ga	82	2.0	Rb	0.66	1.8	Zn	3.7	1.9
Gd	7.2	1.7	Re	0.0047	2.3	Zr	3.2	2.6
Ge	0.49	2.1	Rh	0.85	1.0			

N = 8 except for Cd (2), Eu (7), Hg (7), Os (5), Re (7), Rh (2), Ru (6), Ta (3) and Te (5).

3.2.3 K_d for marine sediments

Two marine sediment sub-samples were obtained from two different depths; 0–5 cm and 30–35 cm (see Section 2.1.3). The solid phase of these samples was analysed using two different digestion methods in order to evaluate the effect on the results. The first method was the same as used for the regolith samples in this study, using *aqua regia* leaching. With the *aqua regia* method the solid phase is not digested completely. This method is considered more appropriate for K_d estimations since the fraction of elements within the mineral structure that is not active in any sorption/desorption processes will not be digested. The second extraction method is the same as has been used in previous analysis conducted for SKB (Engdahl et al. 2008). This method means a total digestion of the mineral structure. It could be expected that this method will generate higher concentrations of especially the mineralogenic elements such as Si and Al. The implication would be higher K_d values when based on total analyses. The K_d values from both these digestion methods are presented in Table 3-5. The median of ratios of K_d total digestion/K_d *aqua-regia* digestion is 2-fold, implying that overall *aqua regia* extracted half of the elements from the solids. The ratio is large (higher than 10) for a few elements; Hf, Pt, Si, Ta and Zr. The ratio is similar for both sediment samples (0–5 and 20–25 cm depth), indicating that the differences were consistent between the two samples.
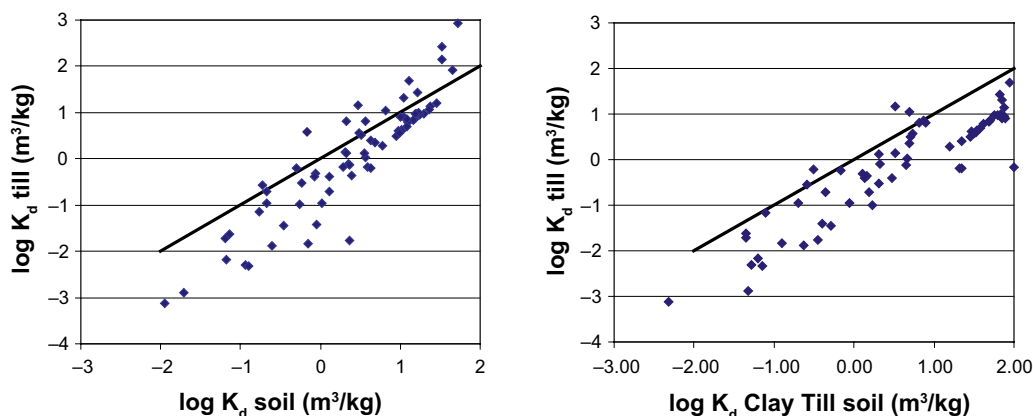
Figure 3-17. *Scatter plot of geometric mean of sandy till K_d (y-axis) versus regolith K_d (x-axis), geometric mean of all regolith samples on the left and geometric mean of the clay till samples only on the right. Each element is a different point.*

Table 3-5. K_d values for marine sediments measured on two samples with two different digestion methods; total digestion and aqua regia leaching. The ratio of these K_d values suggests that the digestion methods only affect the results for a limited number of elements. Ratios higher than 5 have been marked.

Elements	K_d total digestion (0–5 cm)	K_d total digestion (20–25 cm)	K_d aqua regia digestion (0–5 cm)	K_d aqua regia digestion (20–25 cm)	K_d total digestion/ K_d aqua regia digestion (0–5 cm)	K_d total digestion/ K_d aqua regia digestion (20–25 cm)
Ag	37	53				
Al	198	44	812	221	4.1	5.0
As	0.48	0.64	0.48	0.65	1.0	1.0
Au	0.0061	0.0083				
B	0.015	0.0078	0.016	0.016	1.0	2.0
Ba	3.4	0.41	24	3.6	**7.2**	**8.7**
Be	9.3	5.7	21	15	2.3	2.6
Bi	126	50	122	43	1.0	0.9
Br	0.0104	0.0074				
Ca	0.039	0.026	0.082	0.069	2.1	2.7
Cd						
Ce	110	12	200	26	1.8	2.1
Cl	351					
Co	2.8	6.4	2.9	5.9	1.0	0.9
Cr	48	9	111	22	2.3	2.6
Cs	59	49	85	76	1.4	1.5
Cu	38	23	40	22	1.1	0.9
Dy	45	9.3	90	21	2.0	2.3
Er	36	8.9	67	19	1.9	2.1
Eu	80	16	152	33	1.9	2.1
Fe	4.4	3.4	4.1	3.4	0.9	1.0
Ga	240	87	513	228	2.1	2.6
Gd	58	11	13	24	0.2	2.2
Ge	0.58	0.83	5.1	6.3	**8.9**	**7.6**
Hf	7.4	2.6	151	62	**21**	**24**
Hg	17	11	18	11	1.1	1.0
Ho	40	9.9	76	21	1.9	2.2
I						
Ir				1.7		
K	0.066	0.045	0.34	0.33	**5.1**	**7.3**
La	100	11	183	24	1.8	2.2
Li	0.69	0.39	0.73	0.43	1.1	1.1
Lu	26	7.64	50	16	1.9	2.1
Mg	0.050	0.034	0.063	0.063	1.3	1.8
Mn	0.30	0.23	0.30	0.29	1.0	1.3
Mo	0.32	0.21	0.30	0.28	1.0	1.3
Na	0.0028	0.0016	0.0088	0.0091	3.1	**5.6**
Nb	56	15	371	117	6.6	7.7
Nd	76	12	141	24	1.8	2.1
Ni	8.8	6.2	9.3	5.1	1.1	0.8
Os	0.089	2.1				
P	1.3	0.33	1.8	0.55	1.4	1.7
Pb	256	19	245	19	1.0	1.0
Pd			111	73		
Pr	96	12	178	25	1.9	2.1
Pt		0.88		111		**130**
Ra-226	35					
Rb	1.6	1.3	4.2	4.2	2.5	3.3
Re	0.20	0.13	0.15	0.14	0.7	1.1
Rh			1.6	1.1		
Ru			3.7	2.2		
S	0.053	0.027	0.051	0.023	1.0	0.9
Sb	2.0	0.58	2.0	0.66	1.0	1.1
Sc	71	12	169	30	2.4	2.5
Se	0.22					
Si	0.39	0.39	8.6	7.8	**22**	**20**
Sm	62	11	126	24	2.0	2.2
Sn	34	444	34	554	1.0	1.2
Sr	0.027	0.016	0.11	0.082	4.0	5.2

Elements	K_d total digestion (0–5 cm)	K_d total digestion (20–25 cm)	K_d aqua regia digestion (0–5 cm)	K_d aqua regia digestion (20–25 cm)	K_d total digestion/ K_d aqua regia digestion (0–5 cm)	K_d total digestion/ K_d aqua regia digestion (20–25 cm)
Ta	2.8	0.45	493	82	**180**	**180**
Tb	54	11	109	21	2.0	2.0
Te	3.6	1.4	2.3	0.97	0.6	0.7
Th	98	15	213	31	2.2	2.1
Ti	378	80	1,120	304	3.0	3.8
Tl	56	91	120	234	2.1	2.6
Tm	32	9.0	61	18	1.9	2.1
U	7.4	3.6	15	6.9	2.1	1.9
V	14	9.8	29	20	2.0	2.1
W	1.2	1.0	2.6	5.6	2.1	5.6
Y	33	7.9	54	14	1.6	1.7
Yb	31	7.9	58	16	1.9	2.1
Zn	17	13	16	12	1.0	0.9
Zr	4.9	1.9	159	58	**32**	**31**

The marine sediment K_d values based on *aqua regia* digestions are shown in Table 3-6. Because there was only one site sampled, no estimates of variation and no statistical tests within the sediment K_d data are appropriate. Overall, the ratios of K_d (values from 0–5 cm divided by those from 30–35 cm) had a median of 2-fold, indicating that most elements were more soluble at 30-35 cm. This deeper sediment was sampled from below the redox front and was handled to exclude O_2, and so this effect can be attributed to reducing conditions in the deeper samples. Under reducing conditions, oxides of Fe and Mn are relatively soluble, and this effectively decreases the sorption surfaces of the sediment particles.

The relationship of *aqua regia* sediment K_d values to K_d from the agricultural sites is compared in Figure 3-18. The soil K_d values shown in Figure 3-18 are for all regolith types except the sandy till samples. A 1:1 correspondence is not necessarily expected because the media were different. However, it is expected that the slope of the log:log line would be unity. As can be seen in Figure 3-18, the K_d values were similar but there seems to be a consistent trend to a slope different from unity, especially at K_d values above 1 $m^3 kg^{-1}$. This may be because one of the two sediment samples was anoxic. The redox sensitive elements Mn and especially Fe are well below the line, indicating lower K_d in marine sediment than in terrestrial soil. This probably confirms the effect of the reducing environment.

Table 3-6. Marine sediment K_d values, averaging both depths (2 samples) and based on aqua regia digestion ($m^3 kg^{-1}$).

Element	K_d	Element	K_d	Element	K_d
Ag	44	Hf	4.4	Sb	1.1
Al	94	Hg	14	Sc	30
As	0.55	Ho	20	Se	0.22
Au	0.0071	I	0.14	Si	0.39
B	0.011	K	0.055	Sm	26
Ba	1.2	La	33	Sn	120
Be	7.3	Li	0.52	Sr	0.021
Bi	79	Lu	14	Ta	1.1
Br	0.0087	Mg	0.041	Tb	24
Ca	0.032	Mn	0.26	Te	2.2
Ce	37	Mo	0.26	Th	38
Cl	0.0016	Na	0.0021	Ti	170
Co	4.2	Nb	29	Tl	71
Cr	21	Nd	30	Tm	17
Cs	54	Ni	7.4	U	5.2
Cu	30	Os	0.43	V	12
Dy	20	P	0.64	W	1.1
Er	18	Pb	69	Y	16
Eu	36	Pr	34	Yb	15
Fe	3.9	[226]Ra	2.1	Zn	15
Ga	140	Rb	1.4	Zr	3.0
Gd	25	Re	0.17		
Ge	0.69	S	0.038		
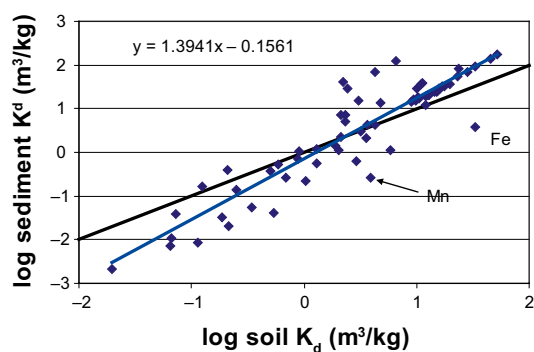
Figure 3-18. Scatter plot of marine sediment K_d versus regolith K_d (excluding the sandy till). Each point is a different element. Note the K_d for Cl is well below the range of these axes. The black line is the 1:1 correspondence, the blue line is the best fit line, and the equation is shown.

3.2.4 Plant/soil concentration ratios

Plant concentration ratios (CRs) are commonly used in assessment models. There are varying formulations; the CR here are concentration in dry plant material divided by the *aqua regia* extracted concentration in the surface layer of dry soil (CR is unitless). The plant samples were collected from 4 sites with barley grain, stem and root collected from all 4 sites and similar samples of wheat collected from 1 of the 4 sites, see Table 2-2. Grain is the plant part consumed by people, and in some cases the stem is used as livestock feed. Roots are of interest when assessing the accumulation of radionuclides in the regolith, but are not linked to the usual exposure pathways. There is a further attribute of these tissues related to how the elements arrive in the plant tissue. Grain is sequestered during growth, inside a sheath of protective plant tissue, so that elements in grain are almost certainly the result of transfer within the plant (note that dust contamination is probable in commercial-scale harvest). Stems (and leaves) may be contaminated with dust and soil splash, and although much of this can be washed off during sampling, absolutely perfect washing is probably impossible. Roots inevitably retain soil particles despite any amount of washing, the only exception being with inner tissue of peeled tuberous crops. In addition, even for absorbed elements, roots often have higher concentrations than grain because some elements are resistant to transport in the plant or may be actively excluded from the grain.

These trends are evident in Table 3-7 and Figure 3-19. Grain always had the lowest CR. In most cases, the root CR was significantly higher than the grain CR, whereas only for a few elements were the grain and stem CR values different.

Table 3-7. Plant/soil concentration ratios for grain, root and stem of barley (*Hordeum vulgare*, 4 sites) and wheat (*Triticum aestivum*, 1 site), and the corresponding results of Scheffe's test of statistical difference ($P < 0.05$).

Element	Grain GM	GSD	Root GM	GSD	Stem GM	GSD	Grain versus root[1]	Grain versus stem[1]
Ag	0.016	1.7	0.061	1.5	0.013	1.7	*	ns
Al	0.0018	7.0	0.11	1.6	0.0019	2.8	*	ns
As	0.0031	2.1	0.047	1.4	0.0056	1.9	*	ns
Au	0.38	1.9	–		0.75	2.3	–	ns
B	0.23	1.4	0.51	1.1	0.47	1.3	*	*
Ba	0.050	1.9	0.26	1.4	0.21	1.7	*	*
Be	0.0016	5.4	0.083	1.6	0.0029	2.7	*	ns
Bi	0.0014	4.2	0.031	1.6	0.0036	2.5	*	ns
Br	0.44	3.6	0.73	2.5	0.63	2.7	ns	ns
Ca	0.065	2.8	0.34	2.2	0.33	2.6	*	ns
Cd	0.00025	2.3	0.0038	1.2	0.00087	1.5	*	*
Ce	0.14	5.9	9.9	1.7	0.48	1.9	*	ns
Cl	6.7	1.8	7.7	2.1	8.9	1.5	ns	ns
Co	0.0012	5.1	0.045	1.6	0.0045	2.5	*	ns
Cr	0.0012	4.9	0.046	1.7	0.0022	3.2	*	ns
Cs	0.0029	3.5	0.056	1.6	0.0026	2.2	*	ns
Cu	0.20	1.3	0.33	1.2	0.15	1.4	*	ns
Dy	0.00056	6.6	0.044	1.6	0.0024	2.3	*	ns
Er	0.00063	6.5	0.051	1.6	0.0027	2.5	*	ns

Element	Grain GM	GSD	Root GM	GSD	Stem GM	GSD	Grain versus root[1]	Grain versus stem[1]
Eu	0.0027	6.3	0.045	1.6	0.0031		*	ns
Fe	0.0024	2.4	0.035	1.7	0.0015	2.5	*	ns
Ga	0.0016	5.4	0.086	1.7	0.0024	1.7	*	ns
Ge	0.063	3.4	0.53	1.8	0.25	1.9	*	ns
Hf	0.032	3.7	0.55	1.9	0.027	4.0	*	ns
Hg	0.025	2.0	0.0923	1.7	0.080	1.8	*	ns
Ho	0.00055	6.9	0.046	1.6	0.0025	2.5	*	ns
I	0.0065	3.4	0.055	2.1	0.026	2.9	*	ns
Ir	0.024	2.3	0.17	4.1	0.020	1.6	ns	ns
K	2.2	1.8	2.2	1.8	2.7	1.8	ns	ns
La	0.00061	5.9	0.043	1.6	0.0024	2.4	*	ns
Li	0.0040	2.4	0.046	1.6	0.0048	1.7	*	ns
Lu	0.00082	5.6	0.053	1.6	0.0027	2.8	*	ns
Mg	0.24	1.5	0.094	1.3	0.13	1.6	*	ns
Mn	0.044	1.8	0.098	1.6	0.052	3.0	ns	ns
Mo	0.73	4.8	0.65	3.0	0.56	3.0	ns	ns
Na	0.30	2.5	1.9	1.7	0.53	3.3	*	ns
Nb	0.0014	6.0	0.076	1.6	0.0017	3.3	*	ns
Nd	0.00053	6.2	0.041	1.6	0.0022	2.2	*	ns
Ni	0.0037	2.9	0.058	1.4	0.0056	2.1	*	ns
Os	0.037	3.2	0.068		0.032	1.5	ns	ns
P	3.9	1.3	1.4	1.5	0.94	1.8	*	ns
Pb	0.0020	3.2	0.042	1.6	0.0046	1.8	*	ns
Pr	0.00055	6.4	0.042	1.6	0.0022	2.2	*	ns
Pt	0.054	3.0	0.45	1.9	0.096	4.9	ns	ns
Rb	0.15	3.1	0.17	1.9	0.11	3.3	ns	ns
Re	0.045	3.6	0.082	3.2	0.059	4.1	ns	ns
Rh	0.19	2.1	0.16	1.4	0.10	1.6	ns	ns
Ru	0.77	13.2	1.3		0.025		ns	ns
S	2.2	2.2	2.0	2.4	1.6	1.9	ns	ns
Sb	0.0039	2.4	0.073	1.3	0.0093	2.3	*	ns
Sc	0.0047	2.9	0.075	1.7	0.0038	2.0	*	ns
Se	0.031	1.9	0.041	1.6	0.021	2.3	ns	ns
Si	0.26	1.7	0.41	1.6	0.65	1.4	*	ns
Sm	0.00048	6.6	0.038	1.6	0.0019	2.3	*	ns
Sn	0.00964	2.6	0.068	1.5	0.015	1.8	*	ns
Sr	0.072	1.9	0.36	1.5	0.35	1.8	*	*
Ta	0.13	2.6	2.4	1.9	0.11	1.6	*	ns
Tb	0.00050	6.5	0.039	1.6	0.0022	2.4	*	ns
Te	0.013		0.079	1.7	0.022	2.4	ns	ns
Th	0.0014	4.8	0.056	1.8	0.0015	3.0	*	ns
Ti	0.0010	7.1	0.067	1.6	0.0014	3.3	*	ns
Tl	0.0023	4.2	0.12	2.0	0.026	2.5	*	*
Tm	0.00067	6.7	0.050	1.7	0.0019	3.1	*	ns
U	0.00056	6.0	0.11	1.4	0.0083	2.9	*	*
V	0.00079	7.0	0.063	1.6	0.0023	3.0	*	ns
W	0.012	6.6	0.10	1.4	0.028	2.7	ns	ns
Y	0.00066	6.3	0.051	1.6	0.0032	2.4	*	ns
Yb	0.00064	7.2	0.052	1.6	0.0025	2.8	*	ns
Zn	0.50	1.3	0.37	1.8	0.28	2.2	ns	ns
Zr	0.021	3.6	0.40	1.9	0.018	3.8	*	ns

For grain, N=5 except Cd (3), Eu (2), Ir (2), Os (4), Pt (4), Re (4), Rh (4), Ru (2), Se (3) and Te (1).

For root, N=5 except Ir (4), Os (2), Ru (2) and Se (4).

For stem, N=5 except Eu (1), Ir (4), Os (4), Pt (4), Rh (2), Ru (1), Se (3) and Te (2).

[1] statistical inferences indicated by ns – not significant (P > 0.05), * – significant at P < 0.05.

The correlations of root and stem CR versus grain CR (Figure 3-19) are instructive. The grain and stem CR values were linearly related, and the 1:1 line shown in Figure 3-19 describes the relationship well, and as indicated by few significant differences in Table 3-7. In contrast, the root CR values diverged from the 1:1 at low CR values, as also observed by Sheppard et al. (2010). These elements include the rare earth elements that are essentially insoluble in soil. At these low CR values, even a very small amount of soil contamination will dominate the plant concentrations. Based on the upper plot in Figure 3-19, it would appear the dry mass of the root samples was about 5% soil. This would not

be easily visible on fibrous root samples during washing. There was probably some soil adhesion to the stem samples as well: about 0.3% of the stem dry mass appears to have been soil, a fairly typical value for leafy plant samples /Sheppard et al. 2010, Sheppard 1995/. This illustrates the importance of using sample preparation methods that are typical of the expected exposure pathway: soil will be included in many plant foods and it is appropriate to recognized that soil is also part of many plant samples. This has a practical aspect as well: in an exposure pathway using empirical CR values, at least some level of incidental soil ingestion is implicit, and one must be careful to not double count forinadvertent soil ingestion by adding too much more soil to the diet.

This study provided the opportunity to examine the expected negative correlation between plant/soil CR and soil K_d (Figure 3-20). A negative correlation is expected because with high K_d, the element is strongly retained by the soil and thus less available for plant uptake. Figure 3-20 confirms this. Sheppard et al. (2010) noted that the relationship was somewhat different for plant-essential versus non-essential elements, in that there were relatively higher CR values for plant-essential elements. This is not evident in Figure 3-20. The computed correlation of log CR versus log K_d in Figure 3-20 was r = –0.45, somewhat lower than the r = –0.7 that has been used in stochastic risk assessments /Sheppard and Sheppard 1989/.
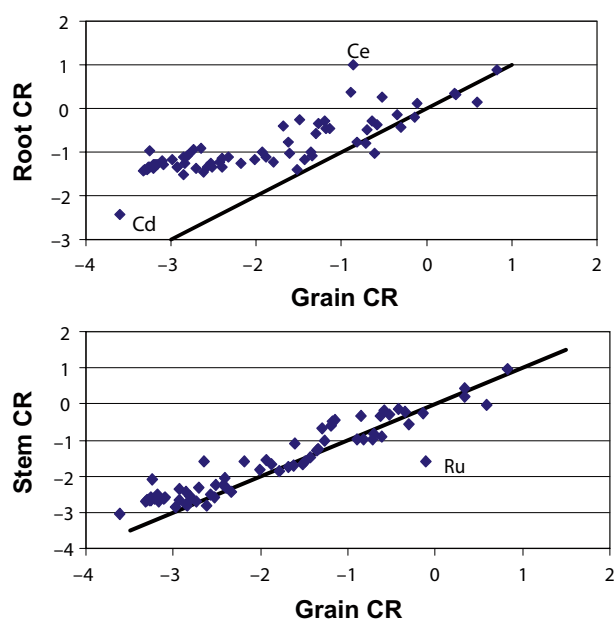
Figure 3-19. *Scatter plot of root and stem CR versus grain CR, averaged for barley and wheat. Each point is a different element. The black line is a 1:1 relationship, deviation away from a 1:1 relationship at low CR is an indication of entrapped soil particles in the plant tissue when analysed.*
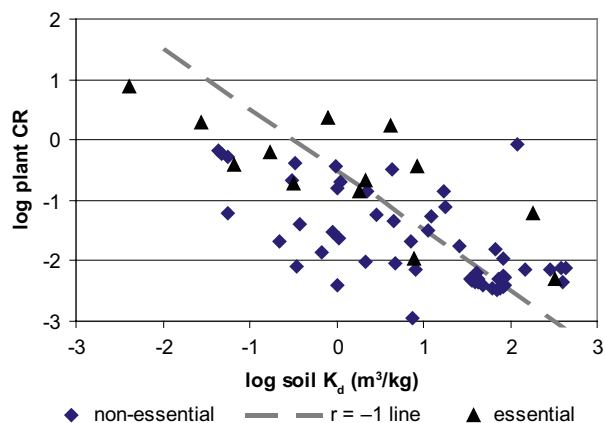
Figure 3-20. *Negative correlation of plant CR (all plant parts and both species) to soil K_d (r = –0.45), differentiating plant-essential and non-essential elements. Each point is a different element. The dashed line is a perfect negative correlation line (r = –1) for comparison.*

4 Discussion

As expected, based on the Central Limit Theorem and empirical evidence, K_d tended to conform to lognormal distributions (e.g. Figure 4-1). There were notable exceptions that were bimodal, as illustrated for Mn (Figure 4-1). To investigate the reason for the bimodal distribution, two groups of soils were differentiated based on K_d for Mn above or below 13 m³ kg⁻¹, and the K_d for Mn was up to 1200-fold different between these groups. The K_d for many other elements were also significantly different between these two groups, these were Al, B, Be, Bi, Br, Ca, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Hf, Ho, La, Lu, Mn, Nb, Nd, Ni, Pb, Pr, Rb, Sc, Sm, Sr, Ta, Tb, Th, Ti, Tm, V, Y, Yb, Zn and Zr.

4.1 K_d versus pH and redox

As already noted, Mn has distinctly lower K_d values for chemically reducing environments versus oxidizing environments. Both Mn and Fe had distinctly different K_d values for two groups of the samples, with the K_d for Mn giving the clearest discrimination. These differences corresponded with regolith type for most samples, but were depth-related in the glacial clay. These groups were also confounded by pH. For example, the two groups, those with low K_d for Mn (< 13 m³ kg⁻¹) and those with high K_d (> 13 m³ kg⁻¹), had corresponding pH values (measured in water) of 5.8 ± 0.9 and 8.0 ± 0.4.

These *a posteriori* regolith groups bear some relationship to the field categorization of the soils, as follows:

Clay till	9 of 10 were high-Mn-K_d, 1 shallow soil (AFM001356) was low-Mn-K_d
Clay gyttja	8 of 8 were low-Mn-K_d
Glacial clay	5 of 6 shallow soils were low-Mn-K_d, 1 (AFM001373) was high-Mn-K_d
	6 of 6 deep soils were high-Mn-K_d
Cultivated peat	10 of 10 were low-Mn-K_d
Wetland peat	10 of 10 were low-Mn-K_d

The soils with low K_d for Mn could be different from those with high K_d for Mn for several possible reasons. Firstly, Mn and Fe (and many of the other elements similarly affected here) would be made more soluble by chemically reducing conditions. These conditions may or may not have been present in the field, and may have been induced in the week-long incubation in the lab. The soils in the lab were wetter than they would normally be in the field, which would help induce anoxia. Additionally, the plastic containers used in the lab may have slowed O_2 diffusion into the samples. The effect of anoxia in soil tends to have a threshold, with a sharp change in soil chemistry once O_2 is depleted.
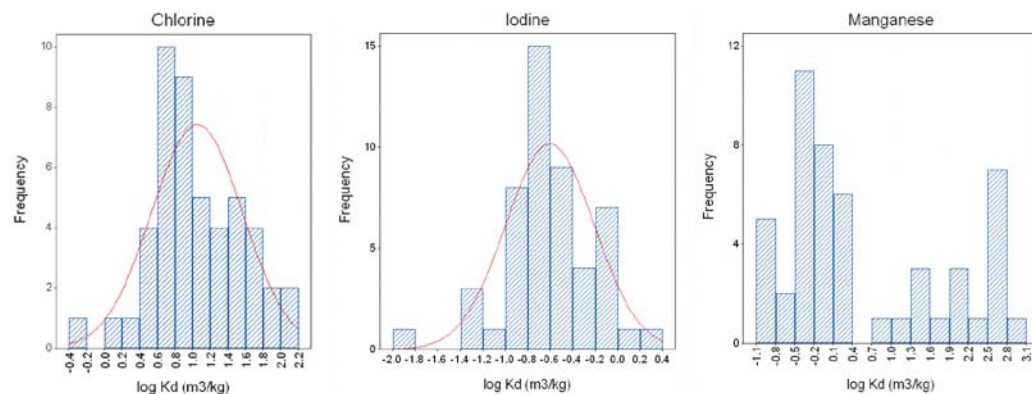
Figure 4-1. Frequency histograms of K_d for selected elements in soil. The red line is the corresponding lognormal distribution. The distribution for Mn is distinctly bi-modal, potentially indicative of a redox effect.

Supporting arguments for a redox effect include that the magnitude of the effect on K_d for Mn was large, 1200-fold. Additionally, a preliminary measurement of K_d in a clay gyttja and a peat sample using nearly identical methods (Appendix C) gave K_d values for Mn 10 to 100-fold higher than in the full study reported here. This seems too large a difference to attribute to spatial variation within a rego-lith type, and it may well be that the samples in the preliminary trial did not pass the redox threshold and become anoxic. Note that K_d for Mn measured in similar soils from Forsmark and Simpevarp using similar methods (Sheppard et al. 2009) gave very similar K_d values for Mn to those reported here.

However, the clay soils sampled had been drained years earlier for cultivation and there was no field evidence of reducing conditions during sampling in these soils. Another explanation of the differentiation by K_d for Mn could be pH. Manganese, Fe and many other elements are more soluble at lower pH. A useful exception is U, which has its highest K_d at near neutral pH and is solubilised at higher pH by U-carbonate complexes. However, U is also redox sensitive. Similarly, anions such as Br might be expected to have lower K_d at higher pH because of competition with hydroxyl ions. In this study, the most acidic soils (clay gyttja with pH 4.8 and the peats with pH 6) had K_d values for Mn of $0.25 \ m^3 \ kg^{-1}$ to $0.76 \ m^3 \ kg^{-1}$. The neutral pH soil (pH 7) in the shallow glacial clay had K_d values for Mn of $2.9 \ m^3 \ kg^{-1}$. The basic soils (clay till and deep glacial clay with pH > 8) had K_d values for Mn of $100 \ m^3 \ kg^{-1}$ to $290 \ m^3 \ kg^{-1}$. This trend is entirely consistent with pH being the controlling factor, but is potentially confounded by redox effects.

Related to pH is the presence of sulphidic soils, especially the gyttja clay where the parent material was deposited as sediments by the Litorina Sea 7,000 to 4,000 BP (Sohlenius and Öborn 2004). In these soils, sulphides may remain present even after drainage, but as they oxidize with time they lower the soil pH and release metals. The metals may be from the specific metal sulphides, especially iron sulphides, or the metals may be co-precipitated or occluded in the sulphides. Additionally, the lower pH resulting from oxidation of sulphides will tend to solubilise many metals, and this lower pH may be in soil micropores and lower than that represented by the bulk-soil pH measurements. The soils studied by Sohlenius and Öborn (2004) that were acid sulphate soils had total S concentrations in the oxidized layer of ~0.15% at 22-cm depth and ~3% at 52-cm depth. The present samples other than the clay till had total S concentrations > 0.2% at 22 cm and > 0.3% at 52 cm depth.

The relationship of K_d to pH is shown in Figure 4-2 for Mn, U and Br. For Mn, the two clusters of samples are evident, but most informative are the data for the glacial clay that had samples in both clusters. They suggest that K_d for Mn was a continuous function of pH, and that an effect of redox was less likely. The K_d for both U and Br showed an opposite response to pH, expected if pH were the operative factor, and these also suggested a continuous function with pH. Note that the clay gyttja soils seemed to deviate from the overall K_d versus pH relationships for U and Br. These obser-vations support the notion that pH was the factor causing the bimodal distributions of K_d. The clay gyttja soils may remain different because of soluble complexes or anion competition with sulphates, and there is a possibility of reducing conditions in micropores.

4.2 Comparison with K_d values reported in earlier studies

The soil K_d data for basic mineral soils from Forsmark are compared to similar soils from agricul-tural areas across Canada (Figure 4-3). They agree at low K_d and some elements diverge at high K_d, where the high K_ds from Forsmark are higher than the corresponding Canadian values. Note that it is most likely that the elements with K_d values below ~1 $m^3 \ kg^{-1}$ (log value 0) are the ones that are sufficiently mobile that they could emerge from an underground disposal facility, and thus agreement at this end of the K_d scale is more important. The divergence at higher K_d is not fully understood, but one explanation is that some of the clay till and glacial clay soils had exceptionally high pH, higher than any of the Canadian soils used in Figure 4-3. Thus, this divergence may be just a continuation of the pH effect to even more basic soils.

Sheppard et al. (2009) measured soil K_d on 7 soils from Forsmark and Simpevarp. Of these, two were acidic clay gyttja soils (their soil sites D from ASM001434 and F from PSM000277) and these had properties comparable to the clay gyttja and the surface layer of the glacial clay here. Two others were acidic peats (their soil sites B from PFM006024 and E from ASM001440), with properties comparable to the peats here. The results of the two studies are compared in Figure 4-4. Given that there was no replication of the soil in Sheppard et al. (2009) and the analytical laboratories were different, the agree-ment is reasonable. Values for Zn are most different, and there is no obvious explanation for this.
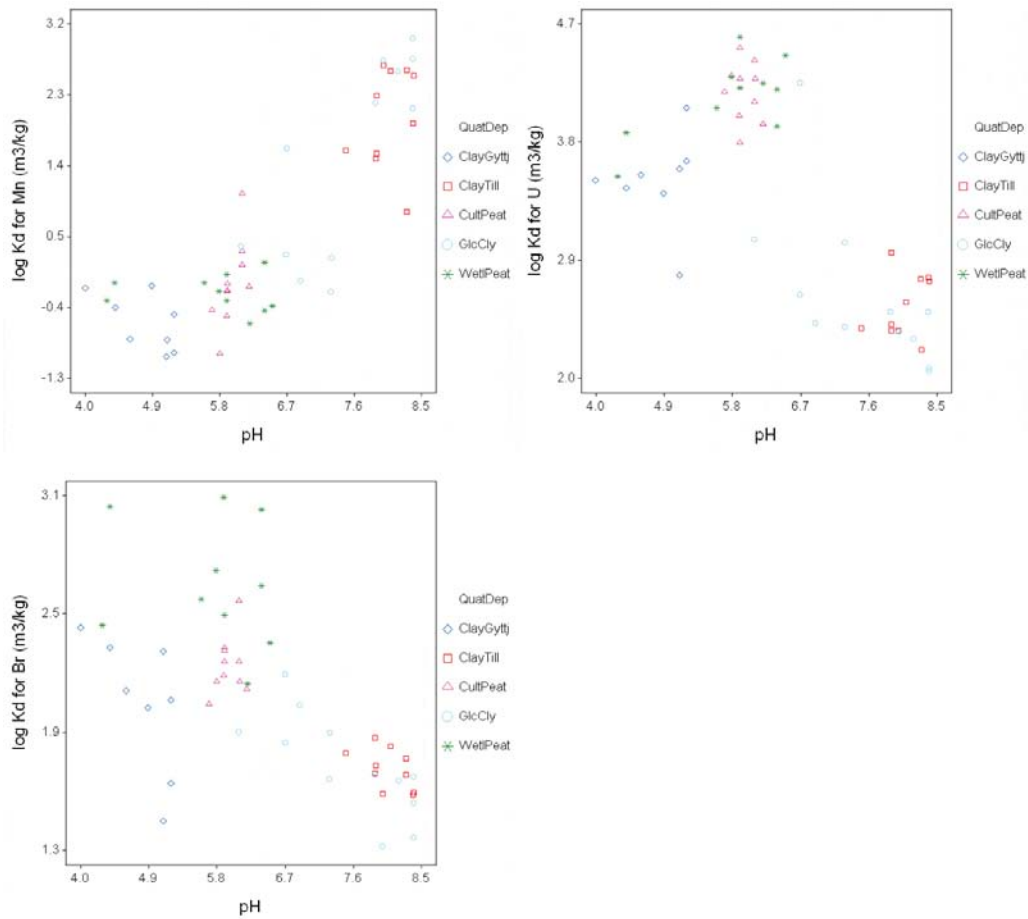
Figure 4-2. *Scatter plot of log K_d versus pH for Mn, U and Br.*
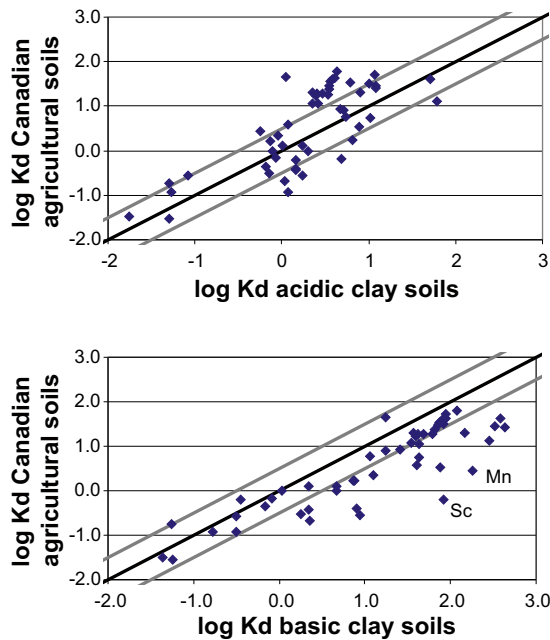
Figure 4-3. *Comparison of soil K_d for acidic and basic clay soils from Forsmark with similar K_d values for ~200 Canadian agricultural mineral soils where the pH was 6.6 ± 1.4. The black line is the 1:1 correspondence and the grey lines are approximately 1 GSD above and below this. Each point is a different element.*
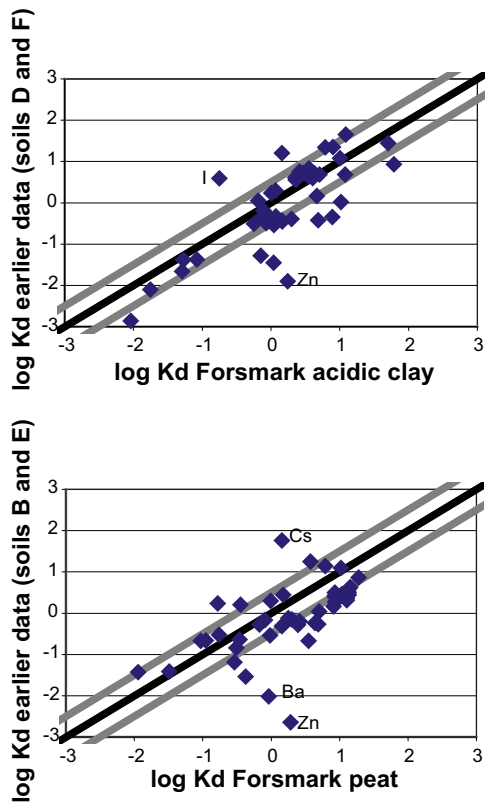
Figure 4-4. *Comparison of soil K_d for soils from Forsmark with similar K_d values for Forsmark and Simpevarp soils reported by Sheppard et al. /2009/. The black line is the 1:1 correspondence and the grey lines are approximately 1 GSD above and below this. Each point is a different element.*

5 Conclusions

The K_d values varied significantly among the regolith sampled, with generally lower K_d values for peat compared to clay soils. There were also clear differences in K_d resulting from differences in soil chemistry within each regolith type. Soil pH was the most important factor, and K_d values for many elements were lower in acidic clay soils than in basic clay soils (all the peat samples were acidic). There were probably effects of organic matter content on K_d, but in this study these were confounded by regolith type and correlation to other soil properties. In general, the K_d values measured here agreed with other compilations.

Although there were only a few samples of sandy till and marine sediment, the K_d values were generally consistent with the corresponding regolith K_d values. The differences that were apparent may be because the sandy till was quite sandy and the marine sediment included an anoxic lower layer.

The plant CR data conformed to expectation. In most cases, the root CR was significantly higher than the grain CR whereas only for a few elements were the grain and stem CR values different. It is evident from consideration of CR for rare earth elements that even with careful washing, some soil material was retained on plant samples. This is a common observation and has implication for exposure pathways analysis.

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Appendix A

K$_d$ data

Table A-1. K$_d$ (m^3 kg^{-1}) of sampled wetlands and agricultural soils – Ag to Ce. Note that these GM and GSD values are across both depths sampled, and in some cases there were statistically significant effects of depth. Table 3-3 should be used to obtain depth-specific GM values.

Sample number	Sampled depth (cm)	Regolith type	Ag	Al	As	Au	B	Ba	Be	Bi	Br	Ca	Cd	Ce
		All GM (GSD)	2.2 (3.0)	33 (8.8)	1.3 (4.2)	0.065 (2.7)	0.066 (2.1)	1.3 (2.1)	2.1 (3.3)	24 (3.9)	0.11 (2.7)	0.19 (2.8)	3.7 (9.4)	20 (5.3)
AFM001356	20–25	Clay till	2.1	510	2.1	0.034	0.080	1.2	7.4	120	0.057	0.093		110
AFM001356	55–55	Clay till	1.0	260	6.9	0.036	0.095	4.2	11	59	0.038	0.50		100
AFM001357	20–25	Clay till	2.5	300	2.7	0.048	0.068	1.5	6.7	56	0.054	0.268	11	89
AFM001357	55–55	Clay till	1.3	160	4.3	0.052	0.080	2.3	5.8	31	0.038	0.79		65
AFM001359	20–25	Clay till	2.9	530	2.3	0.022	0.070	0.91	6.1	85	0.049	0.21	14	180
AFM001359	55–55	Clay till	1.5	640	3.1	0.034	0.064	1.3	5.4	160	0.048	0.60		210
AFM001361	20–25	Clay till	3.6	450	1.4	0.029	0.038	1.0	6.4	160	0.062	0.041	4.5	160
AFM001361	55–55	Clay till	1.1	445	3.8	0.049	0.051	2.0	6.9	83	0.038	0.25	2.1	96
AFM001376	20–25	Clay till	6.1	360	2.9	0.25	0.060	1.6	6.7	93	0.074	0.21	16	130
AFM001376	55–55	Clay till	2.3	140	3.3		0.042	1.3	5.0	30	0.067	0.46		74
	Clay till: GM (GSD)		2.1 (1.8)	340 (1.7)	3.0 (1.5)	0.045 (2.0)	0.062 (1.3)	1.6 (1.6)	6.6 (1.2)	76 (1.8)	0.051 (1.3)	0.26 (2.5)	7.5 (2.4)	110 (1.5)
AFM001362	20–25	Clay gyttja	0.60	0.80	0.13	0.019	0.023	0.26	0.35	0.60	0.028	0.035	0.26	0.6
AFM001362	55–55	Clay gyttja	1.9	4.3	7.3	0.016	0.017	1.2	0.33	28	0.13	0.023	0.04	1.7
AFM001365	20–25	Clay gyttja	2.8	3.1	1.8	0.056	0.036	0.76	1.1	4.6	0.10	0.11	0.34	3.2
AFM001365	55–55	Clay gyttja	4.1	4.8	9.6	0.047	0.031	1.8	0.45	57	0.27	0.038	0.058	1.5
AFM001367	20–25	Clay gyttja	7.6	11	2.7	0.064	0.031	1.2	2.2	7.7	0.12	0.078	0.42	4.2
AFM001367	55–55	Clay gyttja	1.8	9.3	5.4	0.066	0.030	4.9	1.0	23	0.21	0.046	0.11	1.5
AFM001368	20–25	Clay gyttja	7.7	20	8.2	0.067	0.021	0.87	2.3	25	0.043	0.030	0.31	10
AFM001368	55–55	Clay gyttja	1.6	7.1	4.5	0.062	0.026	3.6	0.65	31	0.20	0.038	0.10	2.0
	Clay gyttja: GM (GSD)		2.6 (2.4)	5.4 (2.6)	3.1 (4.1)	0.044 (1.8)	0.026 (1.3)	1.3 (2.5)	0.81 (2.2)	13 (4.3)	0.11 (2.2)	0.044 (1.7)	0.15 (2.4)	2.2 (2.3)
AFM001363	20–25	Glacial clay	1.2	3.9	0.46	0.029	0.020	0.61	1.1	1.5	0.078	0.026	0.28	1.6
AFM001363	55–55	Glacial clay	0.27	2,200	7.0	0.013	0.038	4.6	17	480	0.021	0.35	7.4	430
AFM001369	20–25	Glacial clay	7.4	110	2.6	0.080	0.12	0.82	5.2	28	0.11	0.082		22

Sample number	Sampled depth (cm)	Regolith type	Ag	Al	As	Au	B	Ba	Be	Bi	Br	Ca	Cd	Ce
AFM001369	55–55	Glacial clay	0.16	2,800	6.7		0.11	2.7	15	160	0.034	0.14		360
AFM001371	20–25	Glacial clay	1.5	1.7	0.42		0.022	0.71	1.0	0.75	0.079	0.19	0.53	1.4
AFM001371	55–55	Glacial clay	0.79	61.0	17		0.071	2.3	4.0	`80	0.16	0.34	1.7	40
AFM001372	20–25	Glacial clay	1.2	45	1.9	0.15	0.042	0.83	3.8	27	0.069	0.041		19
AFM001372	55–55	Glacial clay	0.46	1,100	5.8	0.091	0.066	3.2	8.5	130	0.023	0.12		240
AFM001373	20–25	Glacial clay	2.4	180	3.2	0.15	0.060	2.2	8.5	13	0.048	0.29	31	25
AFM001373	55–55	Glacial clay	0.50	480	12	0.15	0.10	4.8	10	54	0.046	1.1		100
AFM001374	20–25	Glacial clay	1.3	100	0.84	0.081	0.058	1.2	7.0	18	0.046	0.1	3.8	13
AFM001374	55–55	Glacial clay	0.18	980	9.4	0.090	0.12	7.1	16	185	0.045	1.1		130
	Glacial clay: GM (GSD)		**0.80 (3.0)**	**150 (10)**	**5.2 (3.5)**	**0.074 (2.3)**	**0.059 (1.9)**	**1.9 (2.3)**	**5.9 (2.6)**	**30 (6.8)**	**0.054 (1.8)**	**0.18 (3.2)**	**2.5 (5.7)**	**37 (6.7)**
AFM001379	20–25	Cultivated peat	4.9	4.7	0.83		0.078	0.81	2.4	16	0.11	0.21	10	14
AFM001379	55–55	Cultivated peat	1.2	8.2	0.27		0.063	0.69	1.6	14	0.20	0.23		23
AFM001381	20–25	Cultivated peat	6.9	8.6	0.89		0.074	0.40	2.5	14	0.15	0.086	5.7	18
AFM001381	55–55	Cultivated peat	5.9	7.1	0.26		0.043	0.28	2.2	16	0.14	0.067		17
AFM001382	20–25	Cultivated peat	4.4	3.6	1.0		0.064	1.2	2.0	7.7	0.18	0.29	7.2	9.3
AFM001382	55–55	Cultivated peat	2.7	3.8	0.43	0.39	0.057	1.3	2.0	5.3	0.21	0.30		5.8
AFM001383	20–25	Cultivated peat	1.4	8.0	0.70	0.33	0.12	1.5	1.6	26	0.18	0.39	39	20
AFM001383	55–55	Cultivated peat		11	0.069		0.089	1.4	0.76	23	0.36	0.50	66	18
AFM001384	20–25	Cultivated peat	1.3	5.7	0.31		0.11	1.5	0.62	16	0.14	0.44	14	13
AFM001384	55–55	Cultivated peat	2.7	6.6	0.25		0.071	1.3	2.7	11	0.13	0.36		10
	Cultivated peat: GM (GSD)		**2.9 (2.0)**	**6.4 (1.4)**	**0.39 (2.3)**	**0.36 (1.1)**	**0.074 (1.4)**	**0.91 (1.8)**	**1.7 (1.7)**	**14 (1.6)**	**0.17 (1.4)**	**0.24 (2.0)**	**16 (2.6)**	**14 (1.5)**
AFM001385	20–25	Wetland peat	2.6	1.5	0.42	0.67	0.035	1.3	0.36	3.2	0.28	0.48	1.5	3.2
AFM001385	55–55	Wetland peat	1.1	2.1	0.17	0.27	0.047	1.8	0.35	7.6	1.1	0.52	4.2	4.8
AFM001387	20–25	Wetland peat	27	5.0	0.14		0.14	1.7	0.79	12	0.37	0.56	18	10
AFM001387	55–55	Wetland peat	3.2	6.5	0.16		0.11	1.3	0.64	8.1	0.53	0.46	42	12
AFM001388	20–25	Wetland peat	12	42	0.86	0.06	0.34	0.49	0.45	27	0.44	0.18	97	29
AFM001388	55–55	Wetland peat	4.3	16	0.39		0.146	1.1	1.0	11	1.1	0.41	34	15
AFM001389	20–25	Wetland peat	42	43	0.38	0.015	0.51	0.33	0.36	24	0.14	0.13		32
AFM001389	55–55	Wetland peat	4.3	46	0.47	0.022	0.31	0.47	0.28	20	0.23	0.19	58	26
AFM001391	20–25	Wetland peat	6.7	12	0.26	0.14	0.17	1.2	0.66	12	0.31	0.44	9.4	13
AFM001391	55–55	Wetland peat	1.4	24	0.28		0.13	1.1	1.6	37	1.2	0.44	100	30
	Wetland peat: GM (GSD)		**5.4 (3.3)**	**11 (3.5)**	**0.31(1.8)**	**0.089 (4.3)**	**0.15 (2.3)**	**0.95 (1.8)**	**0.56 (1.7)**	**13 (2.1)**	**0.45 (2.1)**	**0.34 (1.7)**	**21 (4.2)**	**14 (2.2)**

Table A-2. K_d (m^3 kg^{-1}) of sampled wetlands and agricultural soils – Cl to Hg. Note that these GM and GSD values are across both depths sampled, and in some cases there were statistically significant effects of depth. Table 3-3 should be used to obtain depth-specific GM values.

Sample number	Sampled depth (cm)	Regolith type	Cl	Co	Cr	Cs	Cu	Dy	Er	Eu	Fe	Ga	Gd	Ge	Hf	Hg
		All GM (GSD)	0.011 (3.3)	4.3 (6.0)	13 (4.6)	23 (15)	2.5 (2.7)	13 (4.2)	10 (4.0)	11 (5.6)	33 (7.6)	46 (6.5)	15 (4.3)	0.88 (2.2)	3.7 (5.0)	4.8 (2.8)
AFM001356	20–25	Clay till	0.0052	19	88	650	1.7	60	44		530	440	61	3.9	7.7	6.2
AFM001356	55–55	Clay till	0.0013	42	110	540	2.3	35	29	52	150	200	45	2.2	18	2.2
AFM001357	20–25	Clay till	0.014	20	85	640	1.6	44	44	80	240	240	40	0.6	9.6	13
AFM001357	55–55	Clay till	0.011	32	110	500	1.6	40	38	150	100	120	53	9.5	8.2	1.0
AFM001359	20–25	Clay till	0.0018	13	68	350	1.0	39	33		370	310	53	1.0	3.7	5.5
AFM001359	55–55	Clay till	0.0043	25	81	460	0.83	66	48		400	320	86	1.3	15	4.2
AFM001361	20–25	Clay till	0.0026	18	89	440	1.1	36	27	60	350	110	47	1.4	3.9	4.5
AFM001361	55–55	Clay till	0.0063	23	150	380	1.3	42	32	83	340	170	52	0.47	12	4.0
AFM001376	20–25	Clay till	0.0044	20	43	500	1.9	41	37		230	240	46	0.47	6.5	13
AFM001376	55–55	Clay till	0.0092	21	98	290	1.7	26	18	46	190	180	34	0.60	5.7	9.5
	Clay till: GM (GSD)		0.0047 (2.2)	22 (1.4)	88 (1.4)	460 (1.3)	1.4 (1.4)	42 (1.3)	34 (1.3)	72 (1.5)	260 (1.7)	210 (1.5)	50 (1.3)	1.3 (2.7)	8.0 (1.7)	5.0 (2.2)
AFM001362	20–25	Clay gyttja	0.0038	0.10	0.50	6.5	0.29	0.37	0.26	0.43	0.16	2.4	0.5	0.48	0.042	1.1
AFM001362	55–55	Clay gyttja	0.0050	0.27	9.0	7.3	1.5	1.6	1.4	2.0	10	160	1.8	1.1	2.9	1.4
AFM001365	20–25	Clay gyttja	0.040	0.54	3.9	8.0	0.64	2.4	1.9	2.9	4.6	7.3	2.9	0.62	0.29	4.6
AFM001365	55–55	Clay gyttja	0.014	0.45	11	32	1.9	1.4	1.3	1.5	16	210	1.6	1.0	6.6	1.2
AFM001367	20–25	Clay gyttja	0.022	0.91	8.4	67	0.95	3.3	2.6	3.7	11	45	3.6	0.25	0.64	9.9
AFM001367	55–55	Clay gyttja	0.018	1.1	7.3	97	1.0	1.1	1.0	1.1	20	140	1.2	1.4	2.6	4.4
AFM001368	20–25	Clay gyttja	0.0052	0.77	13	99	2.0	7.6	6.1	10	31	220	9.1	1.3	1.9	8.3
AFM001368	55–55	Clay gyttja	0.013	0.79	9.0	74	1.3	1.7	1.4	1.6	24	180	1.6	0.55	3.0	4.0
	Clay gyttja: GM (GSD)		0.011 (2.3)	0.50 (2.2)	5.9 (2.9)	30 (3.4)	1.0 (1.9)	1.8 (2.4)	1.5 (2.4)	2.0 (2.5)	8.1 (5.4)	59 (5.7)	2.0 (2.3)	0.73 (1.8)	1.1 (5.2)	3.2 (2.4)
AFM001363	20–25	Glacial clay	0.0077	0.56	1.6	25	0.33	1.1	0.91	1.2	1.4	21	1.4	0.8	0.13	1.2
AFM001363	55–55	Glacial clay	0.0006	190	81	230	9.1	240	130		760	3,100	270	2.1	90	0.82
AFM001369	20–25	Glacial clay	0.0094	4.5	18	150	2.2	13	11	33	55	310	17	1.9	2.1	5.1
AFM001369	55–55	Glacial clay	0.0075	160	12	230	4.7	230	160		2,100	530	380	0.6	140	1.1
AFM001371	20–25	Glacial clay	0.0097	3.8	3.1	5.7	0.54	1.2	1.1	1.2	1.2	2.4	1.5	0.33	0.20	1.7
AFM001371	55–55	Glacial clay	0.0026	50	330	360	5.3	19	18	21	530	200	20	1.2	30	3.8
AFM001372	20–25	Glacial clay	0.0042	3.1	11	270	0.80	10	8.6	13	43	89	12	0.5	1.3	5.8
AFM001372	55–55	Glacial clay	0.0031	66	18	190	1.9	140	110		890	260	200	2.6	95	0.70

Sample number	Sampled depth (cm)	Regolith type	Cl	Co	Cr	Cs	Cu	Dy	Er	Eu	Fe	Ga	Gd	Ge	Hf	Hg
AFM001373	20–25	Glacial clay	0.0070	43	79	420	1.9	15	14	16	47	160	17	0.53	3.7	4.4
AFM001373	55–55	Glacial clay	0.0069	85	46	480	4.7	70	52	220	340	360	83	0.82	66	1.1
AFM001374	20–25	Glacial clay	0.0061	4.1	28	340	1.5	6.8	6.4	8.2	44	110	6.5	0.37	2.8	2.6
AFM001374	55–55	Glacial clay	0.0042	86	170	480	3.3	87	70	180	520	880	100	0.81	80	1.3
	Glacial clay: GM (GSD)		**0.0048 (2.2)**	**20 (6.8)**	**26 (4.8)**	**170 (3.8)**	**2.1 (2.7)**	**22 (6.4)**	**18 (5.7)**	**16 (6.3)**	**100 (11)**	**170 (6.2)**	**27 (6.7)**	**0.84 (2.0)**	**8.5 (12)**	**1.9 (2.1)**
AFM001379	20–25	Cultivated peat	0.038	0.86	4.1	6.9	2.4	10	8.8		9.4	11	12	2.2	3.1	12
AFM001379	55–55	Cultivated peat	0.110	2.3	3.7	1.2	2.8	18	14		27	5.4	23	1.1	5.3	8.2
AFM001381	20–25	Cultivated peat	0.0095	1.3	7.4	9.2	3.1	13	11		13	12	16	0.4	3.2	12
AFM001381	55–55	Cultivated peat	0.018	0.60	7.8	1.7	3.7	11	8.7		7.4	10	15	0.6	2.8	13
AFM001382	20–25	Cultivated peat	0.046	1.1	3.3	2.5	1.8	7.3	6.1	11	6.6	3.4	8.6	0.2	1.3	6.9
AFM001382	55–55	Cultivated peat	0.016	1.3	3.4	26	1.6	4.7	3.9	5.4	5.2	10	5.8	0.3	0.89	4.7
AFM001383	20–25	Cultivated peat	0.026	2.8	6.1	7.7	2.7	13	13		19	8.2	18	2.2	3.6	12
AFM001383	55–55	Cultivated peat	0.13	4.0	3.4	2.4	3.4	16	11		42	2.5	24	0.6	4.4	35
AFM001384	20–25	Cultivated peat	0.087	1.4	3.5	1.8	2.6	12	14		14	4.2	11	0.2	4.1	5.9
AFM001384	55–55	Cultivated peat	0.039	1.6	3.6	11	2.5	7.2	6.7	15	8.9	11	8.6	0.5	1.6	7.8
	Cultivated peat: GM (GSD)		**0.038 (2.4)**	**1.5 (1.8)**	**4.4 (1.4)**	**4.5 (2.7)**	**2.6 (1.3)**	**10 (1.5)**	**9.1 (1.5)**	**9.6 (1.7)**	**12 (1.9)**	**6.9 (1.8)**	**13 (1.6)**	**0.58 (2.4)**	**2.7 (1.8)**	**10 (1.8)**
AFM001385	20–25	Wetland peat	0.030	1.0	0.94	0.16	3.4	2.9	2.4	4.1	1.8	2.7	3.3	2.5	0.86	5.0
AFM001385	55–55	Wetland peat	0.055	3.8	1.4	0.16	4.2	4.0	3.8	5.0	3.2	3.0	5.9	0.91	0.73	4.7
AFM001387	20–25	Wetland peat	0.044	1.9	3.6	0.37	5.6	9.1	7.1		7.5	7.5	10	1.0	1.8	20
AFM001387	55–55	Wetland peat	0.046	2.1	3.3	0.45	8.2	12	10		13	10	12	2.5	4.4	79
AFM001388	20–25	Wetland peat	0.0059	2.3	5.9	1.6	31	18	19		8.8	25	16	0.93	3.3	5.3
AFM001388	55–55	Wetland peat	0.0089	2.7	12	1.2	7.6	14	14	33	30	10	15	0.65	4.3	
AFM001389	20–25	Wetland peat		1.6	9.4	0.37	24	16	8.3		2.7	22	26	1.2	2.2	6.7
AFM001389	55–55	Wetland peat		1.3	6.3	0.43	8.5	17	9.9		21	30	17	0.69	3.0	4.2
AFM001391	20–25	Wetland peat	0.020	1.9	2.8	0.60	11	9.3	8.2		12	15	13	1.0	1.9	25
AFM001391	55–55	Wetland peat	0.077	5.2	14	0.60	21	28	22		35	13	28	1.0	4.7	10
	Wetland peat: GM (GSD)		**0.027 (2.5)**	**2.1 (1.6)**	**4.4 (2.4)**	**0.47 (2.1)**	**9.7 (2.1)**	**11 (2.0)**	**8.7 (2.0)**	**8.8 (3.2)**	**9.0 (2.8)**	**11 (2.3)**	**12 (1.9)**	**1.1 (1.6)**	**2.3 (1.9)**	**10 (2.7)**

Table A-3. K$_d$ (m^3 kg^{-1}) of sampled wetlands and agricultural soils – Ho to Nd. Note that these GM and GSD values are across both depths sampled, and in some cases there were statistically significant effects of depth. Table 3-3 should be used to obtain depth-specific GM values.

Sample	Sampled depth (cm)	Regolith type	Ho	I	Ir	K	La	Li	Lu	Mg	Mn	Mo	Na	Nb	Nd
All GM (GSD)			**12 (4.1)**	**0.25 (2.5)**	**0.51 (4.1)**	**0.35 (2.4)**	**18 (4.6)**	**0.59 (5.6)**	**9.0 (3.9)**	**0.54 (3.4)**	**3.9 (18)**	**0.69 (5.8)**	**0.020 (2.3)**	**16 (4.5)**	**16 (4.6)**
AFM001356	20–25	Clay till	50	0.33		0.41	89	1.6	40	1.0	6.2	0.090	0.035	56	68
AFM001356	55–55	Clay till	30	0.23		1.9	52	3.1	26	3.1	340	0.19	0.040	73	50
AFM001357	20–25	Clay till	41	0.31		1.0	78	1.9	36	1.1	30	0.14	0.076	45	51
AFM001357	55–55	Clay till	38	0.17		0.88	68	2.0	31	1.9	87	0.068	0.053	54	62
AFM001359	20–25	Clay till	38	0.19		0.32	79	1.0	24	1.3	36	0.23	0.027	61	66
AFM001359	55–55	Clay till	51	0.15		0.31	140	1.4	33	2.4	410	0.066	0.054	130	120
AFM001361	20–25	Clay till	30	0.38		0.26	56	2.0	24	1.0	39	0.18	0.043	63	49
AFM001361	55–55	Clay till	35	0.15		0.44	68	3.9	23	2.4	460	0.12	0.074	110	63
AFM001376	20–25	Clay till	41	0.31		0.44	82	2.3	38	1.5	190	0.26	0.053	53	59
AFM001376	55–55	Clay till	27	0.24		0.34	61	2.8	16	2.6	390	0.074	0.047	59	52
		Clay till: GM (GSD)	**37 (1.2)**	**0.23 (1.4)**		**0.51 (1.9)**	**74 (1.3)**	**2.1 (1.5)**	**28 (1.3)**	**1.7 (1.5)**	**100 (4.3)**	**0.13 (1.7)**	**0.048 (1.4)**	**67 (1.4)**	**62 (1.3)**
AFM001362	20–25	Clay gyttja	0.32	0.013		0.10	0.61	0.13	0.20	0.11	0.094	0.30	0.0040	0.48	0.51
AFM001362	55–55	Clay gyttja	1.6	1.0		1.1	1.3	0.20	1.6	0.24	0.16	7.3	0.0091	28	1.9
AFM001365	20–25	Clay gyttja	2.2	0.13		1.2	3.3	1.2	1.5	1.9	0.74	2.6	0.039	3.8	2.9
AFM001365	55–55	Clay gyttja	1.4	1.0		1.3	1.2	0.57	1.4	1.2	0.70	26	0.027	38	1.6
AFM001367	20–25	Clay gyttja	3.1	0.20		4.8	4.4	7.3	2.0	2.2	0.33	3.2	0.031	13	3.6
AFM001367	55–55	Clay gyttja	1.1	0.40		5.7	1.7	1.1	0.79	2.6	0.39	12	0.035	20	1.2
AFM001368	20–25	Clay gyttja	7.3	0.16		1.5	8.6	2.8	4.9	0.58	0.11	6.3	0.013	26	8.5
AFM001368	55–55	Clay gyttja	1.5	0.46		4.2	2.0	0.8	1.2	1.0	0.15	12	0.025	25	1.7
		Clay gyttja: GM (GSD)	**1.7 (2.4)**	**0.24 (4.1)**		**1.5 (3.6)**	**2.1 (2.3)**	**0.87 (3.7)**	**1.3 (2.5)**	**0.82 (3.1)**	**0.25 (2.2)**	**5.1 (3.9)**	**0.018 (2.2)**	**12 (4.3)**	**2.0 (2.3)**
AFM001363	20–25	Glacial clay	1.1	0.055		1.1	1.5	9.1	0.78	0.20	0.64	0.30	0.0039	2.0	1.5
AFM001363	55–55	Glacial clay	180	0.13		0.66	350	1.5	80	0.52	530	0.52	0.0087	100	380
AFM001369	20–25	Glacial clay	13	0.12		0.46	20	8.5	8.9	0.45	0.83	0.15	0.014	15	18
AFM001369	55–55	Glacial clay	230	0.11		1.6	350	2.3	120	1.3	130	0.18	0.028	320	310
AFM001371	20–25	Glacial clay	1.2	0.26		0.53	1.4	1.1	1.0	1.9	2.4	0.34	0.024	0.80	1.4
AFM001371	55–55	Glacial clay	20	0.71		6.2	33	3.6	14	3.7	42	3.0	0.060	210	21
AFM001372	20–25	Glacial clay	10	0.13		0.11	16	3.0	7.5	0.37	1.9	0.14	0.013	15	13

Sample	Sampled depth (cm)	Regolith type	Ho	I	Ir	K	La	Li	Lu	Mg	Mn	Mo	Na	Nb	Nd
AFM001372	55–55	Glacial clay	128	0.093		1.1	230	2.0	100	1.6	560	0.056	0.016	170	210
AFM001373	20–25	Glacial clay	14	0.22		0.54	20	1.8	15	1.8	150	0.13	0.092	18	18
AFM001373	55–55	Glacial clay	65	0.19		0.99	96	2.9	39	3.2	990	0.11	0.098	59	99
AFM001374	20–25	Glacial clay	7.0	0.044		0.29	11	1.4	7.2	0.64	1.6	0.11	0.036	18	8.3
AFM001374	55–55	Glacial clay	84	0.45		3.0	110	2.3	61	2.5	380	0.16	0.044	120	100
		Glacial clay: GM (GSD)	**21 (6.1)**	**0.15 (2.2)**		**0.83 (2.9)**	**33 (6.6)**	**2.6 (1.9)**	**15 (5.4)**	**1.1 (2.6)**	**29 (18)**	**0.21 (2.8)**	**0.025 (2.6)**	**31 (6.4)**	**29 (6.7)**
AFM001379	20–25	Cultivated peat	10	0.20		0.17	13	0.09	7.1	0.11	0.36	0.46	0.010	2.6	13
AFM001379	55–55	Cultivated peat	19	0.83	1.3	0.13	21	0.038	11	0.094	0.63	0.89	0.0083	4.0	23
AFM001381	20–25	Cultivated peat	13	0.19		0.31	16	0.14	9.5	0.085	0.29	0.34	0.0056	4.1	16
AFM001381	55–55	Cultivated peat	10	0.24		0.043	14	0.091	7.5	0.043	0.10	0.48	0.0061	6.7	14
AFM001382	20–25	Cultivated peat	7.2	0.30		0.44	9.2	0.32	5.8	0.26	0.76	0.29	0.0090	2.3	8.9
AFM001382	55–55	Cultivated peat	4.6	0.29		0.81	5.8	1.3	3.5	1.1	0.63	0.18	0.019	3.2	5.7
AFM001383	20–25	Cultivated peat	14	0.42	0.10	0.15	19	0.37	14	0.18	2.0	0.48	0.014	5.6	18
AFM001383	55–55	Cultivated peat	19	1.14	1.0	0.16	19	0.23	20	0.26	11	2.7	0.015	6.2	19
AFM001384	20–25	Cultivated peat	13	0.19		0.16	14	0.32	8.0	0.18	1.3	0.50	0.010	4.6	15
AFM001384	55–55	Cultivated peat	6.8	0.22		0.27	9.9	2.0	6.0	0.24	0.71	0.31	0.014	3.6	9.3
		Cultivated peat: GM (GSD)	**11 (1.6)**	**0.33 (1.9)**	**0.51 (4.1)**	**0.20 (2.2)**	**13 (1.5)**	**0.25 (3.4)**	**8.3 (1.6)**	**0.17 (2.4)**	**0.76 (3.5)**	**0.48 (2.1)**	**0.010 (1.5)**	**4.1 (1.4)**	**13 (1.5)**
AFM001385	20–25	Wetland peat	2.9	0.37		0.07	3.8	0.047	2.0	0.28	0.49	1.5	0.017	2.1	3.1
AFM001385	55–55	Wetland peat	4.8	0.85		0.07	4.8	0.053	3.6	0.26	0.81	3.6	0.016	3.1	4.4
AFM001387	20–25	Wetland peat	9.3	0.48		0.23	9.3	0.058	6.5	0.24	0.81	4.0	0.016	5.4	10
AFM001387	55–55	Wetland peat	12	0.72		0.10	12	0.036	8.1	0.23	0.63	8.6	0.014	8.3	12
AFM001388	20–25	Wetland peat	17	0.21		0.026	26	0.079	20	0.10	0.36	4.9	0.0087	14	21
AFM001388	55–55	Wetland peat	14	0.95		0.031	15	0.046	11	0.21	1.5	2.0	0.011	16	15
AFM001389	20–25	Wetland peat	17	0.059		0.014	34	0.045	7.8	0.078	0.24	5.7	0.0091	18	19
AFM001389	55–55	Wetland peat	14	0.20		0.013	29	0.022	15	0.093	0.41	3.4	0.0091	29	22
AFM001391	20–25	Wetland peat	10	0.15		0.033	13	0.059	7.2	0.21	0.49	9.4	0.013	7.3	13
AFM001391	55–55	Wetland peat	28	1.7		0.047	28	0.078	17	0.21	1.06	13	0.016	18	30
		Wetland peat: GM (GSD)	**11 (1.9)**	**0.38 (2.8)**		**0.044 (2.4)**	**14 (2.1)**	**0.049 (1.5)**	**8.1 (2.0)**	**0.18 (1.6)**	**0.60 (1.7)**	**4.6 (2.0)**	**0.013 (1.3)**	**9.2 (2.3)**	**12 (2.1)**

Table A-4. K$_d$ (m^3 kg^{-1}) of sampled wetlands and agricultural soils – Ni to Sb. Note that these GM and GSD values are across both depths sampled, and in some cases there were statistically significant effects of depth. Table 3-3 should be used to obtain depth-specific GM values.

Sample number	Sampled depth (cm)	Regolith type	Ni	Os	P	Pb	Pd	Pr	Pt	Ra226	Rb	Re	Ru	S	Sb
		All GM (GSD)	2.3 (3.2)	0.50 (3.0)	2.9 (1.9)	28 (5.0)	1.7 (3.3)	17 (4.6)	0.17 (–)	3.6 (2.6)	1.9 (11)	0.12 (4.2)	0.83 (3.8)	0.073 (4.3)	0.91 (2.1)
AFM001356	20–25	Clay till	4.1	0.078	2.9	260		76	0.078	13	100	0.21		0.034	0.47
AFM001356	55–55	Clay till	12		3.5	101		54		28	36	0.035	3.2	0.140	0.88
AFM001357	20–25	Clay till	3.7		2.8	160		60		11	37	0.094	0.35	0.075	0.46
AFM001357	55–55	Clay till	7.2	0.085	3.4	55		66		4.1	21	0.053		0.035	0.46
AFM001359	20–25	Clay till	2.2	0.36	3.6	350		76		23	6.5	0.069	1.68	0.037	0.40
AFM001359	55–55	Clay till	3.5		3.5	190		140		20	13	0.028		0.037	0.29
AFM001361	20–25	Clay till	3.1	0.61	1.9	230		57		5.2	14	0.093	2.02	0.022	0.33
AFM001361	55–55	Clay till	6.4		3.3	68		70		5.4	11			0.026	0.30
AFM001376	20–25	Clay till	3.9		4.9	180	4.6	71		5.1	25	0.23	0.088	0.074	0.43
AFM001376	55–55	Clay till	4.7	1.6	3.9	110		58		2.4	31	0.055		0.036	0.24
		Clay till: GM (GSD)	4.5 (1.6)	0.30 (3.7)	3.3 (1.3)	150 (1.8)		70 (1.3)		8.7 (2.3)	22 (2.2)	0.076 (2.1)	0.80 (4.4)	0.044 (1.8)	0.40 (1.4)
AFM001362	20–25	Clay gyttja	0.13		0.58	0.5		0.5		0.87	0.42	0.027	0.049	0.022	0.20
AFM001362	55–55	Clay gyttja	0.33		2.3	3.7		1.8		1.8	1.2	0.10		0.023	0.95
AFM001365	20–25	Clay gyttja	0.45		1.8	4.1		3.0		1.6	2.2	0.026	0.54	0.087	0.70
AFM001365	55–55	Clay gyttja	0.30		3.5	3.8		1.5		3.0	2.8	0.10	1.3	0.064	1.5
AFM001367	20–25	Clay gyttja	0.72	0.17	4.8	6.4	0.43	3.8		3.3	8.5	0.013	2.6	0.038	0.91
AFM001367	55–55	Clay gyttja	0.68		2.7	5.9		1.3		3.5	14	0.049		0.058	1.0
AFM001368	20–25	Clay gyttja	1.0		7.8	24	0.96	9.0		4.3	3.5	0.0079	4.5	0.016	0.95
AFM001368	55–55	Clay gyttja	0.65		3.0	6.8		1.8		6.4	7.9	0.047	0.24	0.043	1.0
		Clay gyttja: GM (GSD)	0.46 (1.9)		2.7 (2.1)	4.5 (2.9)		2.1 (2.3)		2.6 (1.9)	3.2 (3.1)	0.034 (2.5)	0.68 (5.3)	0.038 (1.8)	0.80 (1.8)
AFM001363	20–25	Glacial clay	0.27	0.47	1.5	1.6		1.5		1.9	2.7	0.010		0.010	0.28
AFM001363	55–55	Glacial clay	20	1.20	6.2	230		330		9.8	8.0	0.026	0.86	0.009	2.13
AFM001369	20–25	Glacial clay	2.1		5.2	46		19		2.5	5.0	0.24	0.94	0.044	0.69
AFM001369	55–55	Glacial clay	24	0.17	6.6	700		370		4.8	8.9	0.019		0.004	0.86
AFM001371	20–25	Glacial clay	1.5		1.6	1.1		1.3			2.0	0.077	1.4	0.047	0.50
AFM001371	55–55	Glacial clay	10	0.59	2.7	77		23			25	0.22		0.022	3.6
AFM001372	20–25	Glacial clay	1.1	2.1	3.7	38		14		2.7	8.0	0.21		0.027	0.49
AFM001372	55–55	Glacial clay	11	0.11	6.6	290		250		6.4	7.4	0.039		0.030	1.0

Sample number	Sampled depth (cm)	Regolith type	Ni	Os	P	Pb	Pd	Pr	Pt	Ra226	Rb	Re	Ru	S	Sb
AFM001373	20–25	Glacial clay	5.6		4.8	21		19		4.6	35	0.040		0.035	0.76
AFM001373	55–55	Glacial clay	33		7.6	97		91		16	24	0.064		0.019	1.5
AFM001374	20–25	Glacial clay	1.9	0.68	1.2	26		10		4.3	31	0.062		0.060	0.65
AFM001374	55–55	Glacial clay	17	0.35	8.6	270		110		22	23	0.037	3.1	0.010	1.3
	Glacial clay: GM (GSD)		**5.1 (4.4)**	**0.49 (2.6)**	**3.9 (2.0)**	**48 (7.3)**		**31 (6.8)**		**5.5 (2.2)**	**10 (2.6)**	**0.056 (2.7)**	**1.4 (1.8)**	**0.020 (2.3)**	**0.91 (2.0)**
AFM001379	20–25	Cultivated peat	1.7	0.68	4.1	13		13		1.5	0.34	2.7	2.02	0.056	1.1
AFM001379	55–55	Cultivated peat	2.5	0.73	1.7	28		23		0.81	0.17	3.8	0.088	0.047	0.93
AFM001381	20–25	Cultivated peat	1.8	1.0	5.2	21		17		0.88	0.51	0.031		0.025	0.55
AFM001381	55–55	Cultivated peat	1.7	0.64	1.8	29		15		0.55	0.13	0.10	1.1	0.029	0.44
AFM001382	20–25	Cultivated peat	1.6	1.0	3.9	9.2		9.1		2.0	0.42	0.29	0.40	0.12	0.67
AFM001382	55–55	Cultivated peat	1.2	0.48	1.9	5.8		5.8		3.0	3.3	0.16	0.56	0.15	0.58
AFM001383	20–25	Cultivated peat	2.1		2.9	35		19		5.4	0.66	0.11		0.25	1.8
AFM001383	55–55	Cultivated peat	3.5	0.50	0.62	50		20		4.3	0.27	0.18		0.33	1.4
AFM001384	20–25	Cultivated peat	1.3	0.013	1.6	22		16		3.5	0.19	0.94	1.0	0.28	1.7
AFM001384	55–55	Cultivated peat	1.7		1.7	13		10		3.7	0.85	0.74		0.11	1.1
	Cultivated peat: GM (GSD)		**1.8 (1.4)**	**0.42 (4.2)**	**2.2 (1.9)**	**19 (1.9)**		**14 (1.5)**		**2.0 (2.2)**	**0.42 (2.6)**	**0.34 (4.7)**	**0.59 (3.0)**	**0.10 (2.6)**	**0.92 (1.6)**
AFM001385	20–25	Wetland peat	0.94	1.1	2.9	3.4		3.2		8.0	0.075	0.35	8.7	0.48	2.5
AFM001385	55–55	Wetland peat	2.8	0.73	2.2	7.3	4.8	5.0		4.0	0.068	0.65	1.5	0.51	2.0
AFM001387	20–25	Wetland peat	1.8	0.93	3.1	23		10		2.7	0.20	0.71		0.41	2.6
AFM001387	55–55	Wetland peat	2.3	1.2	2.7	25		12		1.8	0.12	1.19	0.11	0.43	2.1
AFM001388	20–25	Wetland peat	2.9	0.70	6.4	33		27		1.1	0.059	0.17	1.5	4.7	2.3
AFM001388	55–55	Wetland peat	3.7	0.67	2.2	13		16		2.4	0.10	0.61		1.25	2.3
AFM001389	20–25	Wetland peat	2.9	1.2	0.34	71		25		0.78	0.022	0.57		1.22	1.2
AFM001389	55–55	Wetland peat	1.2	0.20	2.9	21		24	0.37	1.1	0.020	0.38		0.76	2.6
AFM001391	20–25	Wetland peat	1.9	1.3	4.8	10		14		2.5	0.052	0.51		0.67	1.6
AFM001391	55–55	Wetland peat	4.1	2.10	6.2	67		29		2.0	0.084	0.83		0.23	3.2
	Wetland peat: GM (GSD)		**2.2 (1.6)**	**0.88 (1.9)**	**2.7 (2.3)**	**19 (2.6)**		**14 (2.1)**		**2.1 (2.0)**	**0.065 (2.0)**	**0.53 (1.7)**	**1.2 (6.1)**	**0.72 (2.3)**	**2.2 (1.3)**

Table A-5. K_d (m³ kg⁻¹) of sampled wetlands and agricultural soils – Sc to U. Note that these GM and GSD values are across both depths sampled, and in some cases there were statistically significant effects of depth. Table 3-3 should be used to obtain depth-specific GM values.

Sample number	Sampled depth (cm)	Regolith type	Sc	Se	Si	Sm	Sn	Sr	Ta	Tb	Te	Th	Ti	Tl	Tm	U
		All GM (GSD)	10.0 (5.5)	1.0 (1.9)	0.21 (2.6)	15 (4.4)	6.5 (2.7)	0.21 (2.4)	2.0 (4.5)	14 (4.3)	2.1 (3.3)	11 (5.1)	52 (6.4)	4.3 (5.3)	10 (4.2)	2.3 (6.5)
AFM001356	20–25	Clay till	104		0.63	65	4.4	0.10	8.8	66	1.8	71	110	44	56	0.56
AFM001356	55–55	Clay till	62	1.5	1.3	47	4.8	0.46	5.2	42	3.5	53	270	44	30	0.59
AFM001357	20–25	Clay till	160	1.1	0.19	46	6.3	0.21	3.2	51	2.6	48	170	32	51	0.89
AFM001357	55–55	Clay till	110	0.87	0.16	60	5.6	0.57	4.1	50	2.1	44	190	21	34	0.55
AFM001359	20–25	Clay till	100		0.24	60	4.5	0.11	3.4	52	1.3	140	480	8.6	27	0.23
AFM001359	55–55	Clay till	79	0.72	0.44	110	4.5	0.32		94	3.8	150	700	9.2	48	0.16
AFM001361	20–25	Clay till	77	0.94	0.37	47	3.5	0.053	0.4	41	1.0	120	480	21	27	0.24
AFM001361	55–55	Clay till	60	0.61	0.57	59	3.2	0.17	6.7	42	2.1	91	470	15	29	0.23
AFM001376	20–25	Clay till	76	0.93	0.64	53	8.8	0.16	2.8	43	3.7	48	210	29	30	0.26
AFM001376	55–55	Clay till	22	0.56	0.80	42	5.6	0.34	2.5	30	0.84	41	200	16	21	0.38
		Clay till: GM (GSD)	77 (1.7)	0.86 (1.4)	0.44 (1.9)	57 (1.3)	4.9 (1.3)	0.20 (2.1)	3.2 (2.4)	49 (1.4)	2.0 (1.7)	72 (1.7)	280 (1.8)	21 (1.8)	34 (1.4)	77 (1.7)
AFM001362	20–25	Clay gyttja	0.31	0.30	0.40	0.5	3.1	0.044	0.097	0.43	0.45	0.37	1.3	0.58	0.25	0.61
AFM001362	55–55	Clay gyttja	3.6		0.24	2.1	5.6	0.033	3.4	1.7	1.2	10	150	0.92	1.6	3.6
AFM001365	20–25	Clay gyttja	2.2	3.3	0.43	2.8	2.6	0.15	0.089	2.6	1.3	2.1	4.8	2.5	1.8	2.5
AFM001365	55–55	Clay gyttja	3.7	1.5	0.38	1.6	5.7	0.088	2.5	1.5	7.2	11.8	220	2.6	1.4	3.2
AFM001367	20–25	Clay gyttja	4.1	2.1	0.51	3.6	5.6	0.12	0.47	3.8	5.8	4.8	22	7.3	2.5	4.4
AFM001367	55–55	Clay gyttja	2.7	1.5	0.47	1.1	6.9	0.12	1.1	1.2	2.6	7.4	60	9.7	0.91	2.8
AFM001368	20–25	Clay gyttja	7.9		0.55	8.5	8.6	0.057	2.0	8.4	1.5	13	96	4.3	5.9	11
AFM001368	55–55	Clay gyttja	3.3		0.42	1.8	7.1	0.086	3.2	1.8	1.2	9.1	83	5.6	1.3	3.9
		Clay gyttja: GM (GSD)	2.7 (2.6)	1.4 (2.5)	0.41 (1.3)	2.0 (2.3)	5.3 (1.5)	0.078 (1.7)	0.84 (4.5)	1.9 (2.4)	1.9 (2.5)	5.0 (3.3)	35 (6.0)	3.0 (2.7)	1.4 (2.5)	3.1 (2.2)
AFM001363	20–25	Glacial clay	1.1	0.45	0.40	1.4	3.2	0.043	0.18	1.3	0.90	1.5	7.1	2.0	0.92	1.1
AFM001363	55–55	Glacial clay	142	1.1	1.2	400	7.8	0.23	101	220	21	150	3,600	20	250	0.22
AFM001369	20–25	Glacial clay	14	0.85	0.089	18	32	0.089	1.0	15	2.0	23	120	5.9	11	0.26
AFM001369	55–55	Glacial clay	110		0.085	360	13	0.80	6.5	310	44	250	360	29	120	0.11
AFM001371	20–25	Glacial clay	2.7	1.6	0.051	1.3	3.3	0.24	0.023	1.3	0.38	0.70	1.9	2.8	1.1	1.1
AFM001371	55–55	Glacial clay	59		0.079	18	20	0.55	2.3	21	5.4	52	1,100	35	17	18
AFM001372	20–25	Glacial clay	13	0.36	0.09	12	14	0.062	1.3	12	3.6	14	90	12	8.2	0.43
AFM001372	55–55	Glacial clay	110	0.67	0.14	220	14	0.63	1.6	200	12	100	1,100	35	113	0.12

Sample number	Sampled depth (cm)	Regolith type	Sc	Se	Si	Sm	Sn	Sr	Ta	Tb	Te	Th	Ti	Tl	Tm	U
AFM001373	20–25	Glacial clay	55		0.27	16	13	0.22	0.63	15	3.0	14	40	74	13	0.32
AFM001373	55–55	Glacial clay	90		0.32	85	6.9	0.76	6.4	89	7.9	56	300	69	68	0.31
AFM001374	20–25	Glacial clay	30	1.9	0.30	7.4	21	0.10	0.45	6.9	3.3	10	49	24	7.6	0.24
AFM001374	55–55	Glacial clay	160	1.3	0.62	100	14	0.78	135.0	110	47	110	800	25	66	0.20
		Glacial clay: GM (GSD)	**32 (5.0)**	**0.89 (1.8)**	**0.19 (2.6)**	**28 (7.1)**	**11 (2.0)**	**0.25 (2.9)**	**2.0 (12)**	**26 (6.6)**	**5.3 (4.3)**	**25 (6.1)**	**150 (9.1)**	**18 (3.2)**	**19 (6.1)**	**0.42 (4.0)**
AFM001379	20–25	Cultivated peat	5.7	1.7	0.85	12	9.4	0.26	2.8	11	1.1	7.2	9.5	0.55	8.1	15
AFM001379	55–55	Cultivated peat	6.0		0.085	17	0.89	0.22	2.8	18	0.54	8.3	19	0.65	13	33
AFM001381	20–25	Cultivated peat	8.9		0.067	16	38	0.092	3.5	15	2.0	11	18	0.64	10	19
AFM001381	55–55	Cultivated peat	5.7		0.058	14	1.1	0.074	4.0	14	8.0	10	23	0.25	9.3	20
AFM001382	20–25	Cultivated peat	3.1	3.2	0.088	8.5	2.5	0.34	1.9	7.8	3.0	4.4	4.5	0.59	6.0	9.8
AFM001382	55–55	Cultivated peat	2.6	1.2	0.063	5.5	1.8	0.35	0.68	5.1	1.6	3.1	7.0	2.1	3.7	6.1
AFM001383	20–25	Cultivated peat	6.1		0.052	20	9.0	0.43	5.4	19	0.61	7.4	13	1.1	12	19
AFM001383	55–55	Cultivated peat	3.3	1.2	0.061	25	1.9	0.51	5.2	28	0.46	4.3	20	1.6	16	26
AFM001384	20–25	Cultivated peat	2.8		0.056	13	2.8	0.49	2.3	13	0.85	7.0	8.2	0.82	10	13
AFM001384	55–55	Cultivated peat	3.4	1.6	0.057	9.4	79	0.39	1.2	8.7	3.2	3.9	10	0.78	6.9	8.5
		Cultivated peat: GM (GSD)	**4.4 (1.5)**	**1.7 (1.5)**	**0.083 (2.3)**	**13 (1.6)**	**4.8 (4.5)**	**0.27 (2.0)**	**2.5 (1.9)**	**13 (1.6)**	**1.4 (2.5)**	**6.2 (1.5)**	**12 (1.7)**	**0.78 (1.8)**	**8.8 (1.5)**	**15 (1.7)**
AFM001385	20–25	Wetland peat	1.0	0.40	0.091	3.2	0.94	0.55	1.5	3.5	0.4	1.2	3.1	0.23	2.4	3.5
AFM001385	55–55	Wetland peat	1.2		0.19	5.2	1.3	0.61	1.5	4.6	0.45	1.2	4.9	0.27	3.2	7.3
AFM001387	20–25	Wetland peat	2.0	2.1	0.26	10	7.9	0.60	5.1	10	10	1.9	13	0.84	7.5	11
AFM001387	55–55	Wetland peat	2.6		0.046	14	8.6	0.48	1.1	13	1.9	2.1	16	0.82	9.0	19
AFM001388	20–25	Wetland peat	3.6		0.056	20	13	0.17	1.6	20	2.5	3.6	51	2.9	34	8.4
AFM001388	55–55	Wetland peat	1.9		0.10	15	17	0.42	1.3	15	4.8	1.6	4.9	2.8	14	16
AFM001389	20–25	Wetland peat	2.0	1.2	0.15	26	23	0.13	2.0	13	0.36	6.4	36	13	7.0	18
AFM001389	55–55	Wetland peat	4.1	0.44	0.27	15	32	0.17		19	0.29	2.6	38	3.7	12	29
AFM001391	20–25	Wetland peat	2.2		0.36	13	1.8	0.46	2.3	13	0.44	2.4	25	0.74	10	16
AFM001391	55–55	Wetland peat	2.5		0.57	26	19	0.42	13.3	27	3.1	3.1	57	0.72	22	40
		Wetland peat: GM (GSD)	**2.1 (1.5)**	**0.82 (2.2)**	**0.16 (2.3)**	**12 (2.0)**	**7.4 (3.6)**	**0.35 (1.8)**	**2.3 (2.2)**	**12 (1.9)**	**1.2 (3.6)**	**2.3 (1.7)**	**17 (2.9)**	**1.2 (3.5)**	**9.2 (2.2)**	**14 (2.0)**

Table A-6. K_d (m^3 kg^{-1}) of sampled wetlands and agricultural soils – V to Zr. Note that these GM and GSD values are across both depths sampled, and in some cases there were statistically significant effects of depth. Table 3-3 should be used to obtain depth-specific GM values.

Sample number	Sampled depth (cm)	Regolith type	V	W	Y	Yb	Zn	Zr
		All GM (GSD)	**12 (4.5)**	**5.9 (2.9)**	**9.4 (4.0)**	**9.8 (4.1)**	**3.0 (3.2)**	**3.2 (4.3)**
AFM001356	20–25	Clay till	10	3.9	43	54	7.2	3.5
AFM001356	55–55	Clay till	33	8.1	23	27	4.7	13
AFM001357	20–25	Clay till	8.1	3.0	38	44	6.8	4.7
AFM001357	55–55	Clay till	21	7.8	28	29	4.8	7.2
AFM001359	20–25	Clay till	12	17	28	27	3.9	2.7
AFM001359	55–55	Clay till	28	12	45	44	4.0	7.3
AFM001361	20–25	Clay till	10	7.8	26	25	4.4	3.0
AFM001361	55–55	Clay till	30	8.4	26	29	4.6	8.2
AFM001376	20–25	Clay till	11	7.1	34	34	6.7	4.7
AFM001376	55–55	Clay till	16	6.9	17	19	9.5	3.8
	Clay till: GM (GSD)		**16 (1.7)**	**7.4 (1.6)**	**30 (1.3)**	**32 (1.4)**	**5.4 (1.3)**	**5.2 (1.7)**
AFM001362	20–25	Clay gyttja	0.45	0.46	0.26	0.21	0.18	0.060
AFM001362	55–55	Clay gyttja	86	12	1.0	1.6	0.29	2.4
AFM001365	20–25	Clay gyttja	4.6	2.3	1.7	1.6	1.5	0.33
AFM001365	55–55	Clay gyttja	160	19	0.94	1.4	0.77	4.6
AFM001367	20–25	Clay gyttja	5.1	6.6	2.3	2.3	1.9	0.56
AFM001367	55–55	Clay gyttja	36	17	0.87	0.84	1.1	1.9
AFM001368	20–25	Clay gyttja	16	23	5.2	5.2	1.2	1.3
AFM001368	55–55	Clay gyttja	30	21	1.1	1.2	0.66	2.0
	Clay gyttja: GM (GSD)		**15 (6.6)**	**7.8 (4.0)**	**1.2 (2.4)**	**1.3 (2.5)**	**0.75 (2.3)**	**0.94 (4.0)**
AFM001363	20–25	Glacial clay	2.0	1.6	0.84	0.8	2.3	0.13
AFM001363	55–55	Glacial clay	540	19	75	115	14	60
AFM001369	20–25	Glacial clay	19	11	9.9	9.6	6.8	1.5
AFM001369	55–55	Glacial clay	240	30	140	170	23	83
AFM001371	20–25	Glacial clay	1.0	0.56	1.2	1.1	2.6	0.19
AFM001371	55–55	Glacial clay	280	4.7	18	15	7.3	40
AFM001372	20–25	Glacial clay	14	11	8.4	7.7	5.2	1.5

Sample number	Sampled depth (cm)	Regolith type	V	W	Y	Yb	Zn	Zr
AFM001372	55–55	Glacial clay	150	33	100	100	14	45
AFM001373	20–25	Glacial clay	17	6.8	13	14	15	3.5
AFM001373	55–55	Glacial clay	92	29	56	51	21	45
AFM001374	20–25	Glacial clay	13	3.2	6.2	7.5	15	2.3
AFM001374	55–55	Glacial clay	140	38	60	61	35	66
	Glacial clay: GM (GSD)		**38 (7.4)**	**8.8 (3.8)**	**17 (5.3)**	**17 (5.7)**	**10 (2.3)**	**6.9 (11)**
AFM001379	20–25	Cultivated peat	2.6	3.5	7.8	8.0	1.3	3.4
AFM001379	55–55	Cultivated peat	3.2	5.6	12	14	0.76	4.1
AFM001381	20–25	Cultivated peat	2.8	5.2	9.7	9.1	1.3	2.5
AFM001381	55–55	Cultivated peat	4.8	4.1	8.3	7.6	0.76	3.1
AFM001382	20–25	Cultivated peat	1.5	2.2	5.6	5.6	0.80	1.2
AFM001382	55–55	Cultivated peat	1.2	1.5	3.8	3.8	1.4	0.81
AFM001383	20–25	Cultivated peat	4.4	7.0	13	12	2.2	3.9
AFM001383	55–55	Cultivated peat	7.4	8.1	13	19	1.3	3.1
AFM001384	20–25	Cultivated peat	3.9	5.0	9.9	11	1.4	3.9
AFM001384	55–55	Cultivated peat	3.2	1.6	6.3	6.2	1.8	1.4
	Cultivated peat: GM (GSD)		**3.1 (1.7)**	**3.8 (1.8)**	**8.4 (1.5)**	**8.7 (1.6)**	**1.2 (1.4)**	**2.4 (1.8)**
AFM001385	20–25	Wetland peat	1.1	2.5	2.3	2.4	0.90	0.77
AFM001385	55–55	Wetland peat	2.0	0.89	3.7	3.8	1.3	1.2
AFM001387	20–25	Wetland peat	5.8	2.0	6.9	7.3	2.1	2.0
AFM001387	55–55	Wetland peat	7.6	2.7	8.8	8.8	1.3	3.7
AFM001388	20–25	Wetland peat	14	9.0	15	15	4.2	4.0
AFM001388	55–55	Wetland peat	18	1.6	12	12	2.8	4.1
AFM001389	20–25	Wetland peat	13	16	13	6.8	16	4.4
AFM001389	55–55	Wetland peat	15	4.0	14	18	7.7	3.6
AFM001391	20–25	Wetland peat	8.6		8.9	10	3.0	2.7
AFM001391	55–55	Wetland peat	17		21	15	3.9	5.3
	Wetland peat: GM (GSD)		**7.7 (2.6)**	**3.2 (2.6)**	**8.9 (2.0)**	**8.5 (1.9)**	**3.0 (2.4)**	**2.8 (1.9)**

Appendix B

Analyses results

Table B-1. Properties of sampled regolith – exchangeable element concentrations.

Sample number	Sampled depth (cm)	Regolith type	Exchangeable acidity (cmol(+)/kg dw)	Exchangeable Mn (cmol(+)/kg dw)	Exchangeable Mg (cmol(+)/kg dw)	Exchangeable Ca (cmol(+)/kg dw)	Exchangeable Na (cmol(+)/kg dw)	Exchangeable K (cmol(+)/kg dw)	Cation Exchange Capacity (cmol(+)/kg dw)	Exchangeable Al (cmol(+)/kg dw)
AFM001356	20–25	Clay till	< 0.2	< 0.003	0.45	18.4	0.03	0.25	19.2	< 0.05
AFM001356	50–55	Clay till	< 0.2	< 0.003	0.38	18.2	0.05	0.23	18.9	< 0.05
AFM001357	20–25	Clay till	< 0.2	< 0.003	0.43	18.4	0.02	0.28	19.1	< 0.05
AFM001357	50–55	Clay till	< 0.2	0.006	0.35	16.7	0.03	0.20	17.3	< 0.05
AFM001359	20–25	Clay till	< 0.2	< 0.003	0.25	18.5	0.03	0.16	18.9	< 0.05
AFM001359	50–55	Clay till	< 0.2	0.006	0.19	15.5	0.02	0.16	15.9	< 0.05
AFM001361	20–25	Clay till	< 0.2	< 0.003	0.26	14.1	0.02	0.16	14.6	< 0.05
AFM001361	50–55	Clay till	< 0.2	< 0.003	0.22	15.8	0.02	0.13	16.2	< 0.05
AFM001363	20–25	Clay gyttja[a]	5.13	0.008	1.50	17.8	0.68	0.17	25.3	< 0.05
AFM001363	50–55	Clay gyttja[a]	< 0.2	< 0.003	1.86	21.1	0.63	0.51	24.1	< 0.05
AFM001376	20–25	Clay till	< 0.2	< 0.003	0.32	21.4	0.02	0.24	22.0	< 0.05
AFM001376	50–55	Clay till	< 0.2	< 0.003	0.25	19.4	0.02	0.16	19.8	< 0.05
AFM001362	20–25	Clay gyttja	9.32	0.021	1.05	7.78	0.28	0.16	18.6	0.35
AFM001362	50–55	Clay gyttja	12.5	0.015	1.08	4.68	0.32	0.14	18.8	1.98
AFM001365	20–25	Clay gyttja	17.4	0.017	0.69	14.3	0.13	0.23	32.8	1.31
AFM001365	50–55	Clay gyttja	19.0	0.008	0.41	3.41	0.24	0.34	23.4	4.05
AFM001367	20–25	Clay gyttja	13.1	0.041	0.54	12.0	0.19	0.19	26.0	0.62
AFM001367	50–55	Clay gyttja	15.9	0.020	0.32	5.54	0.28	0.20	22.3	3.08
AFM001368	20–25	Clay gyttja	12.1	0.057	0.81	12.5	0.26	0.26	25.9	0.34
AFM001368	50–55	Clay gyttja	< 0.2	0.050	0.64	8.24	0.36	0.20	9.50	1.51
AFM001369	20–25	Glacial clay	0.36	0.009	2.18	37.9	0.20	0.27	40.9	< 0.05
AFM001369	50–55	Glacial clay	< 0.2	0.005	1.00	18.9	0.13	0.31	20.4	< 0.05
AFM001371	20–25	Glacial clay	3.31	0.013	1.80	10.1	0.09	0.25	15.6	< 0.05
AFM001371	50–55	Glacial clay	1.99	0.006	3.78	14.8	0.18	0.47	21.2	< 0.05
AFM001372	20–25	Glacial clay	1.06	0.006	0.92	16.0	0.08	0.24	18.3	< 0.05
AFM001372	50–55	Glacial clay	< 0.2	< 0.003	0.55	18.0	0.19	0.26	19.0	< 0.05

Sample number	Sampled depth (cm)	Regolith type	Exchangeable acidity (cmol(+)/kg dw)	Exchangeable Mn (cmol(+)/kg dw)	Exchangeable Mg (cmol(+)/kg dw)	Exchangeable Ca (cmol(+)/kg dw)	Exchangeable Na (cmol(+)/kg dw)	Exchangeable K (cmol(+)/kg dw)	Cation Exchange Capacity (cmol(+)/kg dw)	Exchangeable Al (cmol(+)/kg dw)
AFM001373	20–25	Glacial clay	< 0.2	< 0.003	0.56	21.3	0.03	0.46	22.3	< 0.05
AFM001373	50–55	Glacial clay	< 0.2	< 0.003	0.57	19.0	0.06	0.38	20.0	< 0.05
AFM001374	20–25	Glacial clay	< 0.2	0.007	2.27	30.4	0.10	0.59	33.4	< 0.05
AFM001374	50–55	Glacial clay	< 0.2	< 0.003	1.28	23.5	0.15	0.45	25.4	< 0.05
AFM001379	20–25	Cultivated peat	3.23	0.013	0.36	18.0	0.03	0.06	21.7	< 0.05
AFM001379	50–55	Cultivated peat	5.07	0.012	0.70	31.1	0.04	0.03	36.9	< 0.05
AFM001381	20–25	Cultivated peat	2.32	0.012	0.32	18.3	0.03	0.05	21.0	< 0.05
AFM001381	50–55	Cultivated peat	3.98	0.016	0.55	21.6	0.06	0.03	26.2	< 0.05
AFM001382	20–25	Cultivated peat	3.54	0.008	0.11	22.2	0.01	0.04	25.9	< 0.05
AFM001382	50–55	Cultivated peat	10.6	0.023	0.66	73.8	0.10	0.09	85.3	< 0.05
AFM001383	20–25	Cultivated peat	2.50	0.011	0.55	22.9	0.04	0.06	26.1	< 0.05
AFM001383	50–55	Cultivated peat	2.97	0.010	0.65	20.4	0.05	0.02	24.1	< 0.05
AFM001384	20–25	Cultivated peat	3.21	0.010	0.72	27.3	0.02	0.04	31.3	< 0.05
AFM001384	50–55	Cultivated peat	3.85	0.010	1.07	30.4	0.03	0.03	35.4	< 0.05
AFM001385	20–25	Wetland peat	73.2	0.016	4.30	41.4	0.57	0.42	120	< 0.05
AFM001385	50–55	Wetland peat	62.2	0.014	3.22	41.5	0.56	0.14	108	< 0.05
AFM001387	20–25	Wetland peat	28.4	0.124	3.87	128	0.33	0.24	161	< 0.05
AFM001387	50–55	Wetland peat	26.6	0.163	4.62	119	0.52	0.15	151	< 0.05
AFM001388	20–25	Wetland peat	8.13	0.071	4.93	105	0.99	0.99	120	< 0.05
AFM001388	50–55	Wetland peat	12.0	0.062	5.94	105	1.22	0.40	125	< 0.05
AFM001389	20–25	Wetland peat	6.60	0.089	6.55	75.9	8.26	3.74	101	< 0.05
AFM001389	50–55	Wetland peat	7.17	0.111	6.77	90.2	9.84	1.44	116	< 0.05
AFM001391	20–25	Wetland peat	20.7	0.064	5.17	109	0.47	0.66	136	< 0.05
AFM001391	50–55	Wetland peat	21.0	0.038	4.24	96.7	0.45	0.16	123	< 0.05
PFM007690_1	180	Sandy till	< 0.2	0.0426	0.18	10.0	0.15	0.0561	10.5	< 0.05
PFM007691_1	350	Sandy till	< 0.2	0.0404	0.31	9.6	0.21	0.0652	10.2	< 0.05
PFM007692_1	50	Sandy till	< 0.2	0.0186	0.44	10.8	0.13	0.0536	11.5	< 0.05
PFM007692_2	100	Sandy till	< 0.2	0.0401	0.28	9.9	0.28	0.0676	10.6	< 0.05
PFM007693_1	30	Sandy till	< 0.2	0.0253	0.68	11.4	0.53	0.0777	12.7	< 0.05
PFM007693_2	100	Sandy till	< 0.2	0.0312	0.32	9.9	0.30	0.0511	10.6	< 0.05
PFM007694_1	250	Sandy till	< 0.2	0.0269	0.15	9.5	0.02	0.0550	9.8	< 0.05
PFM007694_2	250	Sandy till	< 0.2	0.0271	0.19	10.2	0.07	0.0507	10.5	< 0.05

[a] site AFM001363 is listed here as originally classified as Clay gyttja, but in the analysis was redefined as Glacial clay.

Table B-2. Properties of sampled regolith – pH, total C, inorganic C and total N.

Sample number	Sampled depth (cm)	Regolith type	pH in H$_2$O	pH in CaCl$_2$	pH in KCl	Total C (%)	Inorganic C (%)	Total N (%)
AFM001356	20–25	Clay till	8.28	7.33	7.37	2.45	0.2	0.25
AFM001356	50–55	Clay till	8.37	7.39	7.79	1.56	1.3	0.08
AFM001357	20–25	Clay till	7.88	7.13	7.51	2.28	0.5	0.19
AFM001357	50–55	Clay till	8.42	7.24	7.92	1.90	1.5	0.05
AFM001359	20–25	Clay till	7.90	7.12	7.52	3.00	0.8	0.22
AFM001359	50–55	Clay till	8.34	7.40	8.00	1.96	1.4	0.06
AFM001361	20–25	Clay till	7.52	7.00	6.86	2.18	0.1	0.22
AFM001361	50–55	Clay till	7.97	7.32	7.66	0.917	0.2	0.08
AFM001376	20–25	Clay till	7.85	7.16	7.52	2.87	0.5	0.23
AFM001376	50–55	Clay till	8.08	7.25	7.66	2.85	0.8	0.16
AFM001362	20–25	Clay gyttja	5.05	4.49	4.06	8.49	–	0.71
AFM001362	50–55	Clay gyttja	4.59	4.13	3.83	7.79	–	0.90
AFM001363	20–25	Clay gyttja[a]	7.29	6.81	4.60	9.97	–	0.89
AFM001363	50–55	Clay gyttja[a]	8.03	7.51	7.77	1.81	1.5	0.07
AFM001365	20–25	Clay gyttja	4.92	4.36	3.93	13.7	–	1.28
AFM001365	50–55	Clay gyttja	3.97	3.58	3.42	6.71	–	0.90
AFM001367	20–25	Clay gyttja	5.20	4.68	4.14	8.79	–	0.92
AFM001367	50–55	Clay gyttja	4.36	3.98	3.56	4.98	–	0.75
AFM001368	20–25	Clay gyttja	5.15	4.75	4.16	8.76	–	0.91
AFM001368	50–55	Clay gyttja	5.14	4.51	3.92	5.84	–	0.82
AFM001369	20–25	Glacial clay	6.86	6.61	6.82	12.1	0.0	1.06
AFM001369	50–55	Glacial clay	8.37	7.46	7.86	3.44	3.7	0.06
AFM001371	20–25	Glacial clay	6.11	5.43	4.17	1.73	–	0.20
AFM001371	50–55	Glacial clay	6.68	6.06	4.33	0.848	–	0.13
AFM001372	20–25	Glacial clay	6.69	6.29	5.14	4.76	–	0.50
AFM001372	50–55	Glacial clay	8.38	7.55	7.84	2.51	2.4	0.06
AFM001373	20–25	Glacial clay	7.91	7.21	7.65	2.37	0.8	0.19
AFM001373	50–55	Glacial clay	8.42	7.52	7.82	2.16	1.9	0.06
AFM001374	20–25	Glacial clay	7.26	6.83	7.42	5.81	0.1	0.60
AFM001374	50–55	Glacial clay	8.22	7.45	7.77	2.55	1.9	0.10

Sample number	Sampled depth (cm)	Regolith type	pH in H_2O	pH in $CaCl_2$	pH in KCl	Total C (%)	Inorganic C (%)	Total N (%)
AFM001379	20–25	Cultivated peat	5.71	5.39	4.88	49.2	–	3.43
AFM001379	50–55	Cultivated peat	5.90	5.61	4.98	51.1	–	2.72
AFM001381	20–25	Cultivated peat	5.94	5.72	4.82	47.2	–	3.57
AFM001381	50–55	Cultivated peat	5.75	5.51	4.70	48.5	–	2.62
AFM001382	20–25	Cultivated peat	5.91	5.55	4.92	49.7	–	3.01
AFM001382	50–55	Cultivated peat	5.90	5.54	4.92	36.3	–	2.07
AFM001383	20–25	Cultivated peat	6.08	5.75	4.83	48.1	–	2.91
AFM001383	50–55	Cultivated peat	6.10	5.66	4.71	52.1	–	2.20
AFM001384	20–25	Cultivated peat	6.10	5.78	5.09	49.6	–	2.84
AFM001384	50–55	Cultivated peat	6.23	5.75	4.94	49.8	–	2.82
AFM001385	20–25	Wetland peat	4.32	3.57	3.79	52.7	–	1.89
AFM001385	50–55	Wetland peat	4.41	3.78	3.54	52.9	–	2.37
AFM001387	20–25	Wetland peat	5.61	5.24	4.53	49.0	–	2.52
AFM001387	50–55	Wetland peat	5.82	5.38	4.75	52.9	–	2.47
AFM001388	20–25	Wetland peat	6.37	6.08	5.11	50.4	–	2.48
AFM001388	50–55	Wetland peat	6.39	5.87	4.68	50.9	–	2.37
AFM001389	20–25	Wetland peat	6.23	6.05	5.11	51.0	–	2.24
AFM001389	50–55	Wetland peat	6.49	6.13	4.72	48.9	–	2.01
AFM001391	20–25	Wetland peat	5.90	5.39	4.65	50.1	–	2.17
AFM001391	50–55	Wetland peat	5.86	5.23	4.37	50.8	–	1.99
PFM007690_1	180	Sandy till	9.23	7.33	8.94	1.09	1.20	< 0.054
PFM007691_1	350	Sandy till	9.26	7.58	8.99	1.17	1.20	< 0.054
PFM007692_1	50	Sandy till	8.55	7.34	8.18	1.39	1.00	< 0.054
PFM007692_2	100	Sandy till	9.19	7.56	8.96	1.24	1.40	< 0.054
PFM007693_1	30	Sandy till	8.53	7.37	8.11	1.72	1.31	< 0.054
PFM007693_2	100	Sandy till	9.1	7.58	8.82	0.99	1.00	< 0.054
PFM007694_1	250	Sandy till	9.02	7.65	8.82	1.16	1.04	< 0.054
PFM007694_2	250	Sandy till	8.94	7.53	8.6	1.04	1.00	< 0.054

[a] site AFM001363 is listed here as originally classified as Clay gyttja, but in the analysis was redefined as Glacial clay.

Table B-3. Properties of sampled regolith – particle size distribution (%) of mineral components.

Sample number	Sampled depth (cm)	Regolith type	Clay < 2 µm	Fine silt 2–6 µm	Medium silt 6–20 µm	Coarse silt 20–60 µm	Fine sand 60 µm–0.2 mm	Medium sand 0.2–0.6 mm	Coarse sand 0.6–2 mm	Gravel 2-20 mm
AFM001356	20–25	Clay till	17	7	9	10	16	19	13	9
AFM001356	50–55	Clay till	29	10	10	9	13	11	8	10
AFM001357	20–25	Clay till	19	7	10	11	17	16	11	9
AFM001357	50–55	Clay till	22	10	11	13	14	13	7	9
AFM001359	20–25	Clay till	14	7	10	10	15	18	11	16
AFM001359	50–55	Clay till	14	9	13	13	17	14	9	11
AFM001361	20–25	Clay till	14	6	8	11	17	21	12	11
AFM001361	50–55	Clay till	12	4	8	10	16	20	13	17
AFM001376	20–25	Clay till	16	6	7	10	15	20	11	13
AFM001376	50–55	Clay till	16	7	10	11	16	20	9	10
AFM001362	20–25	Clay gyttja	10	4	4	2	16	52	12	0
AFM001362	50–55	Clay gyttja	50	15	16	14	2	3	1	0
AFM001363	20–25	Clay gyttja[a]	26	9	9	22	30	2	2	0
AFM001363	50–55	Clay gyttja[a]	59	21	4	3	9	2	1	0
AFM001365	20–25	Clay gyttja	56	18	12	8	5	1	0	0
AFM001365	50–55	Clay gyttja	46	30	10	4	3	3	1	3
AFM001367	20–25	Clay gyttja	53	19	13	7	6	2	1	0
AFM001367	50–55	Clay gyttja	53	22	14	10	2	0	0	0
AFM001368	20–25	Clay gyttja	50	19	12	6	10	2	1	0
AFM001368	50–55	Clay gyttja	52	22	13	10	3	0	0	0
AFM001369	20–25	Glacial clay	35	14	7	6	12	10	11	5
AFM001369	50–55	Glacial clay	55	33	9	1	1	0	0	0
AFM001371	20–25	Glacial clay	41	11	10	8	16	12	2	0
AFM001371	50–55	Glacial clay	64	15	12	8	2	1	0	0
AFM001372	20–25	Glacial clay	24	7	7	11	28	16	3	4
AFM001372	50–55	Glacial clay	53	18	12	13	4	0	0	0
AFM001373	20–25	Glacial clay	34	10	9	7	15	10	8	8
AFM001373	50–55	Glacial clay	39	17	14	9	8	6	5	4
AFM001374	20–25	Glacial clay	51	13	6	2	8	14	4	2
AFM001374	50–55	Glacial clay	63	26	6	2	1	1	0	0
PFM007690_1	180	Sandy till	2.4	3.8	8.7	13.8	20.7	18.1	12.5	20.1
PFM007691_1	350	Sandy till	1.9	3.1	8	17.5	23.3	17.9	11.6	16.8
PFM007692_1	50	Sandy till	2.5	3.7	6.4	7	10.3	15.5	15.5	39.2
PFM007692_2	100	Sandy till	2.1	3.3	4.8	5	9.2	15.6	17.3	42.9
PFM007693_1	30	Sandy till	3.7	4.7	9.1	11.8	13.8	13.2	12.4	31.2
PFM007693_2	100	Sandy till	1.9	3.4	8.2	13.9	17.4	16.6	14.3	24.2
PFM007694_1	250	Sandy till	2.2	3.6	8	12.9	18.7	19	13.2	22.5
PFM007694_2	250	Sandy till	2.1	3.2	8.1	15.3	20.7	19.4	13.3	18

[a] site AFM001363 is listed here as originally classified as Clay gyttja, but in the analysis was redefined as Glacial clay.

Table B-4. Properties of sampled regolith – water content, bulk density and loss on ignition.

Sample number	Sampled depth (cm)	Regolith type	Water content (%)	Dry bulk density (g dw/cm³)	Loss on ignition (%)
AFM001356	20–25	Clay till	14.4	1.94	4.7
AFM001356	50–55	Clay till	13.3	1.99	1.9
AFM001357	20–25	Clay till	15.8	1.76	3.8
AFM001357	50–55	Clay till	13.4	1.93	1.5
AFM001359	20–25	Clay till	13.4	1.46	4.3
AFM001359	50–55	Clay till	6.1	1.72	1.6
AFM001361	20–25	Clay till	10.0	1.65	4.5
AFM001361	50–55	Clay till	7.6	1.73	1.6
AFM001376	20–25	Clay till	16.3	1.65	5.0
AFM001376	50–55	Clay till	9.8	2.07	2.9
AFM001362	20–25	Clay gyttja	39.3	0.89	18.7
AFM001362	50–55	Clay gyttja	56.5	0.55	15.8
AFM001363	20–25	Clay gyttja[a]	43.0	0.78	18,0
AFM001363	50–55	Clay gyttja[a]	33.9	1.17	3.2
AFM001365	20–25	Clay gyttja	43.1	0.7	24.5
AFM001365	50–55	Clay gyttja	59.0	0.56	13.9
AFM001367	20–25	Clay gyttja	41.7	0.78	17.5
AFM001367	50–55	Clay gyttja	57.5	0.58	11.2
AFM001368	20–25	Clay gyttja	45.0	0.72	16.6
AFM001368	50–55	Clay gyttja	60.2	0.55	11.5
AFM001369	20–25	Glacial clay	41.6	0.8	20.6
AFM001369	50–55	Glacial clay	25.0	1.49	2.8
AFM001371	20–25	Glacial clay	21.0	1.59	4.1
AFM001371	50–55	Glacial clay	27.3	1.43	3.8
AFM001372	20–25	Glacial clay	42.2	0.89	9.4
AFM001372	50–55	Glacial clay	25.9	1.42	1.9
AFM001373	20–25	Glacial clay	17.9	1.78	4.5
AFM001373	50–55	Glacial clay	17.3	1.76	2.7
AFM001374	20–25	Glacial clay	28.4	1.33	9.6
AFM001374	50–55	Glacial clay	24.3	1.45	3.3
AFM001379	20–25	Cultivated peat	75.4	0.22	85.6
AFM001379	50–55	Cultivated peat	81.2	0.18	85.5
AFM001381	20–25	Cultivated peat	67.1	0.3	83.0
AFM001381	50–55	Cultivated peat	75.3	0.21	85.5
AFM001382	20–25	Cultivated peat	74.3	0.28	83.9
AFM001383	20–25	Cultivated peat	75.4	0.25	84.6
AFM001383	50–55	Cultivated peat	82.6	0.14	90.3
AFM001384	20–25	Cultivated peat	68.2	0.32	83.7
AFM001384	50–55	Cultivated peat	70.1	0.29	83.6
AFM001385	20–25	Wetland peat			95.7
AFM001385	50–55	Wetland peat			97.0
AFM001387	20–25	Wetland peat			88.3
AFM001387	50–55	Wetland peat			92.8
AFM001388	20–25	Wetland peat			92.7
AFM001388	50–55	Wetland peat			92.3
AFM001389	20–25	Wetland peat			94.5
AFM001389	50–55	Wetland peat			93.1
AFM001391	20–25	Wetland peat			92.3
AFM001391	50–55	Wetland peat			93.3
PFM007690	1.80	Sandy till	0.001		0.00
PFM007691	3.50	Sandy till	0.001		0.00
PFM007692	0.50	Sandy till	0.002		0.01
PFM007692	1.00	Sandy till	0.001		0.01
PFM007693	0.30	Sandy till	0.002		0.01
PFM007693	1.00	Sandy till	0.001		0.01
PFM007694	2.50	Sandy till	0.001		0.00
PFM007694	2.50	Sandy till	0.001		0.01

[a] site AFM001363 is listed here as originally classified as Clay gyttja, but in the analysis was redefined as Glacial clay.

K$_d$ pre-study

In order to test sampling and analysis methodology and to ensure that detection limits were sufficiently low to receive reliable results, a pre-study was conducted. Three samples were collected in the Forsmark area, one clayey till, one gyttja and one peat sample. The till sample was taken from an arable land at Storskäret within the Forsmark site investigation area (close to one of sampling sites of the main study). This sample was taken at approximately 25 cm depth in a spade dug hole. The gyttja sample was taken with an Edelman corer in the vicinity of the lake Gällsboträsket within the Forsmark site investigation area. This site is located in the vicinity of a small lake with a surrounding wetland area and not an agricultural land as the gyttja samples from the main study. The peat sample was taken from a wetland in the vicinity of one of the sampling sites of the main study using a Russian corer. This site is comparable to the wetland sites from the main study. At this site the groundwater table was situated at the ground surface.

The samples were sent to ALS Scandinavia AB in Luleå for elemental analysis in plastic containers. In order to receive enough pore water the till sample was incubated in the same way as the samples in the main study by adding water to a syringe filled with soil sample. Drops of water were added to the sample until the water started to drop out of the incubation tube. This method was not possible to use for the gyttja sample due to the high clay content. The low permeability of the sample caused the added water to stay on top of the sample instead of penetrating down though the sample. Due to this the decision to mix water into the soil in a plastic container was taken. A small volume of water was added until the apparent field capacity was reached. After this the wet gyttja sample was placed in a closed syringe and left for incubation for one week. The peat sample was already at field capacity and the element analysis of pore water could be conducted without any incubation. These samples were centrifuged without any additional handling.

After centrifugation, total concentration of elements (stable as well as radioactive isotopes) in pore water and in solid phase of the three soil samples were analysed. The resulting K$_d$ for the three samples are presented in Table C-1, Table C-2 and Table C-3, respectively, together with the results of the corresponding K$_d$ values from the main study. When these results were compared to the results from the main study some differences were found.

As can be seen in Table C-1 the difference between K$_d$ from the pre-study and the main study was not significant for the till samples. For the till samples the same incubation method was used for both samples. The ratio between these two results indicates that the results were within one order of magnitude from each other.

In Table C-2 the results from the gyttja analysis are presented. The ratio between the K$_d$ values from the pre-study and the K$_d$ from the main study indicate that there are differences between the two studies. The ratios above 10 are marked in Table C-2. No ratios were below 0.1. This indicate that the results from the pre-study gave higher K$_d$ values for several elements (Be, Cd, Co, Mn, S and Zn), meaning that the concentration of these elements in pore water were lower in the pre-study.

In Table C-3 the K$_d$ values for peat in the pre-study and the K$_d$ values for peat in the main study are compared. As for the gyttja, several of the elements (Be, Br, Co, Cr, Cs, Cu, Fe, I, Mn, Na, Ni, Rb and Zn) had higher K$_d$ values in the test study than from the main study (the ratio above 10 are marked in Table C-3). As for the gyttja this indicates that the pore water concentrations were higher for these elements in the samples from the main study. The K$_d$ value for Mn were higher in the pre-study, but both indicate that the environment was reducing for the peat sample according to the *a priori* classification. This is consistent with the general understanding of the site since the groundwater level at the sites was at ground surface.

Table C-1. Results from the pre-study and the main study for clayey till. The ratio between the results can be used as an indication of the differences between the two results.

Element	K_d pre-study	K_d main study	Ratio of pre-study/ main study	Element	K_d pre-study	K_d main study	Ratio of pre-study/ main study
Ag	3.3	3.2	1.04	Nb	17	55	0.30
Al	280	420	0.67	Nd	47	58	0.81
As	0.37	2.2	0.17	Ni	1.3	3.3	0.38
Au		0.05		Os		0.26	
B	0.07	0.06	1.09	P	1.6	3.1	0.51
Ba	1.00	1.2	0.83	Pb	73	230	0.32
Be	18	6.6	2.73	Pd		4.6	
Bi	20	96	0.21	Pr	58	67	0.86
Br	0.03	0.06	0.42	Pt		0.08	
Ca	0.11	0.14	0.77	Ra-226		9.6	
Cd		10		Rb	5.3	24	0.22
Ce	95	130	0.73	Re		0.12	
Cl				Ru		0.57	
Co	2.4	18	0.14	S	0.03	0.04	0.81
Cr	28	72	0.39	Sb	0.25	0.42	0.60
Cs	280	500	0.56	Sc	53	100	0.53
Cu	1.8	1.4	1.29	Se		0.98	
Dy	28	43	0.65	Si	0.05	0.37	0.14
Er	23	37	0.61	Sm	44	54	0.82
Eu	58			Sn		5.2	
Fe	108	330	0.33	Sr	0.11	0.12	0.88
Ga		240		Ta	1.00	2.5	0.40
Gd	32	49	0.65	Tb	31	50	0.63
Ge		1.1		Te		1.9	
Hf	2.8	5.9	0.47	Th	41	77	0.54
Hg	4.5	7.6	0.59	Ti	207	250	0.83
Ho	25	39	0.64	Tl	3.67	24	0.15
I	0.08	0.30	0.28	Tm	23	36	0.63
K	0.06	0.43	0.13	U	0.17	0.37	0.47
La	68	76.	0.89	V	4.8	10	0.48
Li	1.0	1.7	0.59	W	5.3	6.4	0.83
Lu	18	32	0.56	Y	21	33	0.63
Mg	0.51	1.2	0.42	Yb	22	35	0.63
Mn	8.3	35	0.24	Zn	17	5.6	3.06
Mo	0.02	0.17	0.11	Zr	1.9	3.6	0.53
Na	0.04	0.04	0.86				

Table C-2. Results from the pre-study and the main study for gyttja clay. The ratio between the results can be used as an indication of the differences between the two results. All ratios above 10 are marked.

Element	K_d pre-study	K_d main study	Ratio of pre-study/main study	Element	K_d pre-study	K_d main study	Ratio of pre-study/main study
Ag	3.8	3.1	1.21	Na	0.014	0.016	0.88
Al	13	4.8	2.71	Nb	14	5	2.80
As	1.2	1.5	0.83	Nd	8.8	2.6	3.39
Au		0.05		Ni	4.4	0.45	9.72
B	0.25	0.03	9.26	Os		0.17	
Ba	1.9	0.67	2.82	P	2.3	2.5	0.92
Be	67	1.2	**56**	Pb	12	4.3	2.68
Bi	5.2	4.8	1.08	Pd		0.64	
Br	0.42	0.06	7.07	Pr	9.1	2.7	3.37
Ca	0.19	0.05	3.88	Pt			
Cd	12	0.33	**35**	Ra-226		2.1	
Ce	12	3	3.91	Rb	5.0	2.3	2.17
Cl		0.01		Re		0.016	
Co	47	0.44	**107**	Rh			
Cr	18	3.8	4.80	Ru		0.75	
Cs	90	24	3.75	S	0.7	0.033	**21**
Cu	4.1	0.77	5.37	Sb	0.47	0.59	0.80
Dy	7.0	2.2	3.18	Sc	4.8	2.1	2.26
Er	6.0	1.7	3.53	Se		1.3	
Eu	8.8	2.6	3.37	Si	0.063	0.47	0.13
F				Sm	9.2	2.5	3.67
Fe	26	3.9	6.60	Sn		4.4	
Ga	58	21	2.76	Sr	0.29	0.082	3.54
Gd	7.5	2.6	2.88	Ta	0.17	0.3	0.56
Ge		0.55		Tb	6.9	2.4	2.86
Hf	1.3	0.35	3.67	Te		1.5	
Hg	1.3	4.5	0.30	Th	6.3	2.6	2.42
Ho	6.1	2	3.06	Ti	45	11	4.09
I	0.57	0.09	6.30	Tl	20	2.6	7.69
In				Tm	5.0	1.6	3.13
Ir				U	3.4	3	1.13
K	1.0	0.94	1.10	V	11	3.6	3.10
La	9.7	3	3.24	W	2	3.6	0.56
Li	3.8	1.3	2.91	Y	5.9	1.5	3.94
Lu	5.0	1.3	3.85	Yb	5.8	1.4	4.15
Mg	0.59	0.72	0.81	Zn	17	0.9	**18.9**
Mn	19	0.22	**86**	Zr	1.4	0.35	4.08
Mo	0.67	2	0.33				

Table C-3. Results from the pre-study and the main study for wetland peat. The ratio between the results can be used as an indication of the differences between the two results. All ratios above 10 are marked.

Element	K_d pre-study	K_d main study	Ratio of pre-study/main study	Element	K_d pre-study	K_d main study	Ratio of pre-study/main study
Ag	67	12	0.56	Na	0.22	0.012	**18.6**
Al	105	11	9.55	Nb	40	7.3	5.48
As	1.5	0.35	4.37	Nd	60	11	5.45
Au		0.095		Ni	20	1.93	**10.4**
B	0.62	0.17	3.68	Os		1.02	
Ba	1.1	0.83	1.38	P	8.0	2.5	3.20
Be	24	0.5	**48.6**	Pb	75	18	4.17
Bi	55	12	4.58	Pd			
Br	3.3	0.29	**11.5**	Pr	63	12	5.28
Ca	0.44	0.31	1.43	Pt			
Cd		13		Ra-226		2.1	
Ce	67	13	5.13	Rb	1.7	0.064	**26.8**
Cl		0.02		Re	2.7	0.41	6.50
Co	35	1.7	**20.6**	Rh		–	
Cr	60	3.5	**17.1**	Ru		3.6	
Cs	20	0.46	**43.5**	S	3.1	0.94	3.29
Cu	1,080	11	**98.2**	Sb	0.69	2	0.34
Dy	45	9.3	4.84	Sc	19	2	9.29
Er	38	7.4	5.20	Se		1	
Eu		4.1		Si	0.094	0.15	0.63
F		–		Sm	70	12	5.83
Fe	360	5.2	**69.2**	Sn		5.3	
Ga		11		Sr	0.38	0.32	1.17
Gd	45	11	4.09	Ta		2.2	
Ge		1.2		Tb	47	10	4.67
Hf	5.0	1.8	2.78	Te		1.1	
Hg		9.8		Th	22	2.6	8.33
Ho	36	9.6	3.75	Ti	157	18	8.73
I	3.6	0.2	**18.0**	Tl	4.5	1.4	3.21
In				Tm	35	8.4	4.17
Ir				U	11	9.9	1.06
K	0.22	0.045	4.93	V	8.8	6.2	1.41
La	47	13	3.59	W	4.8	5.1	0.94
Li	0.47	0.056	8.36	Y	44	7.7	5.71
Lu	30	6.8	4.41	Yb	40	7.1	5.70
Mg	0.26	0.16	1.65	Zn	44	3.3	**13.2**
Mn	5.3	0.44	**12.0**	Zr	7.5	2.4	3.13
Mo	0.84	4.4	0.19				

Analysis of Ra-226

One of the main purposes for the pre-study described in Appendix C was to ensure the measure Ra-226 in both solid phase and porewater. Ra-226 analysis had not been done by SKB in previous K_d-studies. Three laboratories were involved in the study, ALS Scandinavia, Laboratory in Luleå, ALS laboratory in Czech Republic and Risö National Laboratory in Denmark. At both Risö and ALS in Czech Republic radiometric methods were used while ALS in Luleå used mass spectrometry.

The results from the analyses are presented in Table D-1 and are reasonably consistent for the solid phase. The results deviated most for the clayey till. The highest values were always from ALS in Czech Republic and the lowest from Risö. ALS in Luleå was the only laboratory that could reach sufficiently low detection limits to analyse Ra-226 in pore water. The decision was therefore taken to do the rest of the Ra-226 analysis at ALS in Luleå. Since all other elements were measured at this laboratory, additional handling of the samples could also be avoided. ALS in Luleå used ICP-SFMS method as describe in Sections 2.2.2 and 2.2.3.

Table D-1. Results from the Ra-226 test analysis.

	Risö National Laboratory	ALS Czech Republic	ALS Luleå
Solid phase (Bq/kg dw)			
Clayey till	16	58	26
Gyttja	50	67	63
Peat	8.8	< 30	11
Pore water (Bq/m³)			
Clayey till	–	–	7.4
Gyttja	–	–	19
Peat	–	–	7.4
K_d (m³/kg dw)			
Clayey till			3.5
Gyttja			3.4
Peat			1.5