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Variations of soil profile characteristics due to varying time spans since ice retreat in the inner Nordfjord, western Norway

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Abstract

In the Erdalen and Bødalen drainage basins located in the inner Nordfjord in western Norway the soils have been formed after deglaciation. The climate in the uppermost valley areas is sub-arctic oceanic and the lithology consists of Precambrian granitic orthogneisses on which Leptosols and Regosols are the most common soils. The Little Ice Age glacier advance affected parts of the valleys with the maximum glacier extent around AD 1750. In this study five sites on moraine and colluvium materials were selected to examine the main soil properties to assess if soil profile characteristics and pattern of fallout radionuclides (FRNs) and environmental radionuclides (ERNs) are affected by different stages of ice retreat. The Leptosols on the moraines are shallow, poorly developed and vegetated with moss and small birches. The two selected profiles show different radionuclide activities and grain size distribution. The sampled soils on the colluviums outside the LIA glacier limit became ice-free during the Preboral. The Regosols present better-developed profiles, thicker organic horizons and are fully covered by grasses. Activity of ^{137}Cs and ^{210}Pb$_{ex}$ concentrate at the topsoil and decrease sharply with depth. The grain size distribution of these soils also reflects the difference in geomorphic processes that have affected the colluvium sites. Significant lower mass activities of FRNs are found in soils on the moraines than on colluviums. Variations of ERNs activities in the valleys are related to characteristics soil mineralogical composition. These results indicate differences in soil development that are consistent with the age of ice retreat. In addition, the pattern distribution of ^{137}Cs and ^{210}Pb$_{ex}$ activities differs in the soils related to the LIA glacier limits in the drainage basins.

1 Introduction

Glacial retreat in the cold regions of Northern Europe is a general trend that has intensified over the last decades. In the Nordfjord region (western Norway) this trend is also observed and the magnitude of glacial retreat in the Erdalen and Bødalen valleys has reached its fastest rate over the last century in recent years (e.g., Winkler et al., 2009; Laute and Beylich, 2013). The retreat of ice from glaciated valleys causes important changes in geomorphic processes of glacial erosion, but also has an impact on the hydrological resources by changing runoff and associated sediment transport as well as on the formation of soils on the newly exposed surfaces.

The landscapes of Norwegian fjords reveal the inheritance of glacial processes since the Last Glacial Maximum (LGM). The Little Ice Age (LIA) glacier advance also affected parts of the Norwegian valleys (Bickerton and Matthews, 1993; Laute and Beylich, 2012, 2013). Amongst the main glacial deposits colluviums and moraines are surface formations resulting from the evolution of slopes and the ice retreat. In the glacial valleys these formations are representative of newly exposed material conditioned by former glaciations and deglaciation. Moraine ridges formed during and after the maximum extent of the Little Ice Age (LIA) with the maximum glacier extent around AD 1750 (Bickerton and Matthews, 1993). On the newly exposed glacial deposits the soils have been forming and as a result of processes related to ice retreat different soil types are developed. Soil properties might be characteristic of materials and processes and could reflect different ages of ice retreat. In this study we aim to characterize the soils formed on colluvium and moraine material to apply a multiproxy approach to elucidate if elemental composition and radionuclide tracers together with other main soil properties could be indicative of soil development and in this way be related to stages of ice retreat. To this purpose we selected two glacial valleys representative of the inner Norfjord region, the valleys of Erdalen and Bødalen and sampled five sites on two main geomorphic elements, moraine and colluvium, to examine within the soil profile main soil properties, elemental composition and fallout (FRNs) and environmental radionuclides (ERNs).

2 Material and methods

2.1 The study area

The inner Nordfjord region is located in western Norway at the western side of the Jostedalsbreen ice cap (Fig. 1). Climate is sub-arctic oceanic in the uppermost parts of tributary valleys draining into the fjord. The mean annual air temperature at 360 m a.s.l. is 5.5 °C and the mean annual areal precipitation is 1500 mm in the drainage basins of Erdalen and Bødalen (Table 1) (Beylich and Laute, 2012; Laute and Beylich, 2013).

The lithology in the valleys consists of Precambrian granitic orthogneisses with migmatisc and dioritisc composition (Table 1). Within the higher part in Bødalen (glacier area) there is a small area of quartzmonzonit outcrops (Lutro and Tveten, 1996).

The landforms and processes in the study area are characteristic of glacial valleys. The detailed geomorphological maps (Laute and Beylich, 2012) shown in Figs. 2 and 3 present the main deposits identified in the valleys and their genesis. The main contemporary denudational surface processes and the limits of the LIA moraines are also identified in the maps together with the locations of the soil profiles studied.

A total of five sites corresponding to soils developed on different surface formations, namely moraines and colluvium as the more representative formations of the glacier valleys and representing different stages of ice retreat were selected for collecting soil profiles. Two profiles were established on moraines in the Bødalen valley (PB1 and PB2) and the other three profiles were established on colluvium materials in the Erdalen (PE1, PE2) and Bødalen (PB3) valleys. The profiles on the moraines are located inside the LIA glacier limit; the moraine material is in general characterized by diamicton. The two sites represent different stages of ice retreat, thus PB1 became ice-free since ca. AD 1930 but PB2 became ice free earlier at about AD 1800 (see Bickerton and Matthews, 1993). Both sites have a vegetation cover composed of mosses and small birches and can be considered quite stable regarding surface soil processes as they are on gentle slopes. The soils on the moraines are Leptosols; they are poorly developed with almost no horizon differentiation and with high content of rock fragments.

The colluvium sites, located outside the LIA glacier limit, are characterized by slope processes accumulating both fine and coarser material at the slope foot derived from slope wash, avalanches, debris flows and rock falls. The soils correspond to Regosols that are deeper and better developed than soils on the moraines and are covered by grass. The sites became ice-free during the Preboral deglaciation. Considering the age of ice retreat the oldest is PB3 in Bødalen that became ice-free around 10 000 yr ago. This profile is on a hillslope located beneath the Tindefjell glacier and is more influenced by glaciofluvial and outwash processes rather than rockfall activity and also presents a high avalanche activity. Of the studied sites PB3 had the strongest anthropogenic impact through animal husbandry, as sheep grazing occurs since approx. 1800 although with less intensity since 1930 (T. Lopez, personal communication, 2011). Of the profiles in Erdalen, PE4 had higher rock-fall activity and became ice-free earlier than PE3 that was ice-free since ca. 9800 yr BP (see Nesje, 1984; Matthews et al., 2008).

2.2 Soil sampling and analyses

To collect the soil samples of the soil profiles five pits of 20 cm × 20 cm were excavated down to a depth of 20–27 cm. Samples were extracted at depth intervals of approx. 5–6 cm by using a 5 cm diameter cylinder.

The soil samples were air-dried, ground, homogenized and quartered, to pass through a 2 mm sieve. General soil properties analysed in the fraction < 2 mm were pH, soil organic carbon (SOC) at 310° (active carbon fraction, ACF) and 550° (stable carbon fraction, SCF) and soil texture. Analysis of the clay, silt and sand fractions was performed using laser diffraction particle size analyser. Prior to the analysis the organic matter was eliminated with H_2O_2 (10 %) heated to 80 °C and samples were disaggregated with sodium hexametaphosphate (40 %), stirred for 2 h and dispersed with ultrasound for a few minutes. The pH (1 : 2.5 soil : water) was measured using a pH-meter.

The contents of soil organic carbon, both active and stable carbon fractions, were analysed by the dry combustion method using a LECO *RC-612* multiphase carbon analyser designed to differentiate forms of carbon by oxidation temperature (LECO, 1996) in a sub-sample of the < 2 mm fraction that had been ground to a very fine powder with a mortar and pestle. According to López-Capel et al. (2008) the decomposition of the most thermally labile components of SOC is released at approximately 300–350 °C during thermal decomposition because they are rapidly and easily burnable, the active and decomposable fraction (ACF) while decomposition of more refractory and stable carbon (SCF) occurs at higher temperatures (420–550 °C).

The analysis of the total elemental composition was carried out after total acid digestion with HF (48 %) in a microwave oven. Samples were analysed for the following 28 elements: Li, K, Na (alkaline), Be, Mg, Ca, Sr (light metals), Cr, Cu, Mn, Fe, Al, Zn, Ni, Co, Cd, Tl, Bi, V, Ti and Pb (heavy metals), B, Sb, As (metalloids), and P, S, Mo and Se. Analyses were performed by atomic emission spectrometry using inductively coupled plasma ICP. Concentrations, obtained after three measurements per element, are expressed in $\mathrm{mg\,kg^{-1}}$.

The methods used in the analysis of radionuclides are described in detail elsewhere (Navas et al., 2005a, b). Radionuclide activity in the soil samples was measured using a Canberra high resolution, low background, hyperpure germanium coaxial gamma detector coupled to an amplifier and multichannel analyser. The detector had a relative efficiency of 50 % and a resolution of 1.9 keV (shielded to reduce background), and was calibrated using standard samples that had the same geometry as the measured samples. Subsamples of 50 g were loaded into plastic containers. Count times over 24 h provided an analytical precision of about ±3–10 % at the 95 % level of confidence. Activities were expressed as $\mathrm{Bq\,kg^{-1}}$ dry soil.

Gamma emissions of ^{238}U, ^{226}Ra, ^{232}Th, ^{40}K, ^{210}Pb, and ^{137}Cs (in $\mathrm{Bq\,kg^{-1}}$ air-dry soil) were measured in the bulk soil samples. Considering the appropriate corrections for laboratory background, ^{238}U was determined from the 63 keV line of ^{234}Th, the activity of ^{226}Ra was determined from the 352 keV line of ^{214}Pb (Van Cleef, 1994); ^{210}Pb activity was determined from the 47 keV photopeak, ^{40}K from the 1461 keV photopeak; ^{232}Th was estimated using the 911 keV photopeak of ^{228}Ac, and ^{137}Cs activity was determined from the 661.6 keV photopeak. The ^{210}Pb (half-life = 22.26 yr) is integrated by the "in situ"-produced fraction from the decay of ^{226}Ra (Appleby and Oldfield, 1992) and the upward diffusion of ^{222}Rn in the atmosphere, which is the source of ^{210}Pb$_{ex}$. Spectrometric measurements were performed a month after the samples were sealed, which ensured a secular equilibrium between ^{222}Rn and ^{226}Ra. The ^{210}Pb$_{ex}$ activities were estimated from the difference between the total ^{210}Pb activity and the ^{226}Ra activity.

ANOVA test was used to analyse the statistical differences in the means of the study parameters.

3 Results

3.1 Characteristics of the soil profiles

The soil profiles in the Bødalen and Erdalen drainage basins are acidic with pH ranging from 4.45 to 5.85 and the predominant soil textures are sandy loam. Contents in SOC are low in average (2.03 %) although highly variable ranging from 0.03 to 14.39 %. The contents of ACF are always higher than the SCF especially in the colluvium profiles. There are clear differences between the properties of the soil profiles on the moraines and on colluviums (Table 2). The latter are significantly less acidic and have higher SOC contents. Comparing with the Leptosols on the moraines, the soils on the colluvium are deeper and better developed with a rich organic A horizon, whereas the soils on the moraines do not present horizon differentiation. Soil samples of the moraines have higher sand contents and lower silt contents than samples of the colluvium but clay contents are similar and low.

The most abundant elements in the studied profiles are Al, Fe, Na, and K ($\overline{x}$: 47 071, 27 608, 25 205 and 23 723 mg kg^{-1}, respectively), Ca and Mg are also major components ($\overline{x}$: 10 492, 7497 mg kg^{-1}, respectively), followed by Ti, B and P ($\overline{x}$: 3942, 1948 and 1068 mg kg^{-1}, respectively), Mn, Sr and S ($\overline{x}$: 448, 279 and 266 mg kg^{-1}, respectively), and Cr, V, Zn, Ni, Tl, Pb and Bi ($\overline{x}$: 90, 54, 47, 43, 39, 28 and 23 mg kg^{-1}, respectively) whereas Li, Sb, Be and Mo have the lower contents ($\overline{x}$: 8.4, 2.4, 1.3 and 0.7 mg kg^{-1}, respectively) and As and Cd were not detected in the study samples.

The mean contents of Al are similar in colluvium and moraine profiles although the variation range is higher in the colluvium profiles (Table 4). Of the major elements mean Fe, Ca and Mg contents are significantly lower in the moraine profiles whereas the opposite is observed for Na and K. In lower concentration ranges (91–6500 mg kg^{-1}), the mean contents of Sr, S, Mn, P and Ti are significantly lower in samples of the moraines than in the colluvium ones, but the opposite is found for B that is much higher in the moraine samples. In minor concentrations (ranges between 5 and 330 mg kg^{-1}), the contents of Tl, V, Zn, Ni and Cr are significantly lower in moraine samples that in turn have significantly higher contents of Pb and Be. Other trace elements like Mo and Sb have significantly lower contents in moraine samples likewise Li, Bi and Cu, although for the latter differences are not significant.

Most of elements were directly correlated among them and correlations were stronger in the colluvium profiles. However, Na, K, Pb, and Be were inversely correlated with the rest of elements and directly correlated between them.

The radioisotope mass activities (Bq kg^{-1}) were 28.1–64.9 for ^{238}U, 12.6–47.7 for ^{226}Ra, 12.6–83.7 for ^{232}Th, 652–1320 for ^{40}K, b.d.l.–118 for ^{210}Pb, b.d.l.–102.4 for ^{210}Pb$_{ex}$, and 1.2–346 for ^{137}Cs. The mean contents of FRNs are much lower in the soils of the moraines although differences are not significant (Table 3). The mean ^{137}Cs content is half in the moraine samples than in the colluvium ones and mean ^{210}Pb$_{ex}$ contents are six times lower in the moraine samples. The range of variation of ^{137}Cs and ^{210}Pb$_{ex}$ in the samples of the colluviums is much larger than that of the moraines. Apart from ^{210}Pb, the ERNs contents are significantly higher in the moraine samples.

The correlations established among the radionuclides with the soil properties in the moraine profiles show that ^{137}Cs is related directly and significantly with SOC and ACF contents ($r = 0.902$, $r = 0.939$, respectively) but inversely with the pH ($r = -0.947$) and the silt and clay fractions ($r = -0.822$, $r = -0.808$, respectively). However, in the colluvium profiles ^{137}Cs was only significantly correlated with SCF content ($r = 0.852$) and the correlations with the fine fractions were direct but not significant. Similar relationships were observed between ^{210}Pb$_{ex}$ and the soil properties although the only significant correlation was that with the SCF content (r = 0.765) in the colluvium profiles.

In the colluvium profiles in spite that only few correlations of ERNs with soil properties were significant, the type of correlations were similar for ^{232}Th and ^{40}K, as both radionuclides were directly related with the fine fractions (^{232}Th $r = 0.811$, $r = 0.709$) but inversely related with the soil organic carbon and the sand contents (^{40}K with SOC and ACF contents, $r = -0.648$, $r = -0.671$, respectively); whereas the opposite was true for ^{226}Ra and ^{238}U. However, in the moraine profiles the type of correlations was different and not significant.

3.2 Distribution of soil properties and elements in the profiles

The vertical distribution of main soil properties, radionuclide and element contents in the study soils show very distinctive patterns in the moraine and the colluvium profiles (Fig. 4). The soil organic carbon (SOC) distribution down the profiles of moraine soils is quite homogeneous and contents are much lower than in the colluvium profiles. The PB1 profile has the lowest SOC (below 0.1 %), most in the active form with almost negligible amounts of the stable carbon fraction. The vertical distribution of SOC contents in the colluvium profiles show decreasing trends, which are more marked in PB3. The PE2 profile shows a large SOC enrichment at the 10–14 cm interval depth, most of it as active form (ACF reaches 12.7 %). The pH profiles show little variations with depth both in the moraine and the colluvium profiles and values are slightly lower at the topsoil than at deeper layers.

The abundance of sand fractions is general in the study profiles, but differences in the depth distribution arisen, thus sand contents decrease with depth in PB1 that is paralleled with clay content increases in this moraine profile characterized by diamicton which is matrix supported. This pattern is not observed in the other moraine profile (PB2) that has very high contents of sand with homogeneous depth distribution. The colluvium profiles of Erdalen have comparable depth distributions of the grain size fractions, with large predominance of sand fractions. However, the PB3 profile of Bødalen shows a quite distinct distribution with increasing sand contents down the profile and conversely decreasing clay contents with depth.

The depth distributions of the chemical elements are considerably more homogeneous in the soil profiles of the moraines than those of the colluviums (Fig. 5). The contents of most chemical elements in the moraine profiles almost do not vary with depth. Exceptions are some trace elements, namely Sb, Mo, Cu, and B and major elements K, Al, and Fe. In the profile PB2 Cu, V and Fe vary more than in PB1 where Al varies the most with depth. In contrast the profiles of the colluviums exhibit larger variations in the element depth distributions and show clearly distinctive patterns between profiles. The profile PB3 shows decreasing trends in the contents of most elements, apart from Na and B. In profile PE2 the high increase in the SOC content (14 %) at 10–15 cm depth is associated with variations in the contents of most elements, which mostly decreases sharply but the opposite is seen for Mo, Cu and S whose contents increase. In profile PE1 the largest variations in the element contents appear at the soil surface where there is high SOC (4 %) in combination with low sand content. Most elements show lower contents at the top layer and decreases are high for Sb, Li, Bi, Tl, V, Zn, Ni, Cr, Mg, Fe, but conversely increases are recorded for B and Pb.

3.3 The vertical distribution of radionuclides

The mass activities of ^{137}Cs and ^{210}Pb$_{ex}$ down the profiles show different patterns in the moraine and the colluvium profiles (Fig. 6). The moraine profiles have homogeneous depth distributions of ^{137}Cs with lower contents in PB1 (range: 2.3–30.2 Bq kg^{-1}) than in PB2 (20–84 Bq kg^{-1}). The ^{210}Pb$_{ex}$ that is almost negligible in PB2 is only detected in the topsoil of PB1. Therefore, the typical decay pattern of the FRNs mass activities with depth is not found in these moraine profiles.

The colluvium profiles exhibit the characteristic ^{137}Cs exponential decay with depth typical of undisturbed soils. The decay is more marked in PB3 and PE1 profiles, the ^{137}Cs mass activities decrease sharply from the topsoil that have very high values (266–346 Bq kg^{-1}, respectively) to deeper layers (1.64–2.75 Bq kg^{-1}, respectively). The mass activities of ^{210}Pb$_{ex}$ are considerably lower and the radionuclide is only found in the upper layers, therefore the penetration of ^{210}Pb$_{ex}$ is much lower than that of ^{137}Cs that is detected at 25 cm in PE1.

The depth distributions of ERNs show different patterns, thus that of ^{226}Ra and ^{232}Th are very similar in the moraine profiles but this is not the case in the colluvium profiles that even exhibit opposite trends in profile PE1. The ^{40}K mass activities vary largely and values are higher in the profiles of Bødalen. The ^{238}U is the less variable (CV: 21 %) and it does not show any clear pattern in its depth distribution.

All profiles show disequilibrium in the uranium and thorium series. Under secular equilibrium the activity ratios of ^{238}U/^{226}Ra will be approximately 1, however values in the profiles exceed 1 largely (range 1.27–2.98) and the colluvium profile PB3 shows the greater disequilibrium. Similarly, although most environmental samples have ^{232}Th/^{226}Ra activity ratios around 1.1 (Evans et al., 1997) all soil profiles have ratios higher than 1.1. Deviations are much higher in profile PB3 (3.34–4.25) in spite that in topsoil layers of the colluvium profiles there are depleted levels of ^{232}Th.

4 Discussion

On the colluvium the Regosols are better developed with a rich organic A horizon, whereas the Leptosols on the moraines are shallow and do not present horizon differentiation. The higher content of coarse fractions in the Leptosols is in accordance with the physical processes such as rock disintegration by the action of ice that are more relevant in the moraines than in the colluviums. These features result in distinctive soil properties that affect the pattern distribution of stable elements and radionuclides in the profiles. The inverse correlations found between Na, K, Pb, and Be with the rest of elements and the direct correlations between them suggest a different mineralogical source to the rest of elements. The range of variation of ^{137}Cs and ^{210}Pb$_{ex}$ is linked to the high contents recorded in the organic horizons of the Regosols of the colluviums, while the highest content of ERNs, in the Leptosols, apart from ^{210}Pb, is related to mineralogical and geochemical differences in the composition of the moraine materials.

The correlations among the radionuclides with the soil properties support the different characteristics of FRNs in the Leptosols of recently deglaciated moraines affected by LIA compared with the Regosols outside the LIA. In the colluvium profiles the type of correlations that were similar for ^{232}Th and ^{40}K suggest that both radionuclides are related with clay minerals. Whereas the opposite was true for ^{226}Ra and ^{238}U what might indicate a common and different mineralogical source to that of ^{232}Th and ^{40}K. However, in the moraine profiles the type of correlations was different and not significant. The direct and significant correlations among the ERNs in the moraine profiles denote a common origin (Fairbridge, 1972). However, the contrary was observed in the colluvium profiles suggesting that soil processes have affected the ERNs distribution, which are not so closely linked with their primary mineralogical origin as in the moraine profiles.

The higher values and decreasing distribution of SOC in Regosols illustrates a higher degree of soil evolution reflecting the oldest age in terms of ice-free retreat of the colluvium sites that became deglaciated approx. 10 000 yr ago. This is further confirmed by the higher percentages of the SCF by compared to its content in the moraine profiles. The SOC rich layer at the 10–14 cm interval depth in PE2 (see Fig. 4) might correspond to a buried soil that is likely to have occurred at this site due to intense and frequent rock-fall activity.

The grain size distribution in the profiles helps to interpret the role of physical processes such as rock disintegration on soil development in cold environments (Navas et al., 2008). In general, these soils are characterized by the abundance of sand content, especially in the topsoil. However, the low values and increasing contents of sand with depth in PB3 (see Fig. 4) are related with the decreasing trends in the contents of most elements, apart from Na and B. This site, which is in a hillslope located beneath the Tindefjell glacier, is more influenced by glaciofluvial and outwash processes rather than rockfall activity that likely affect the particle size distribution in the profile. In addition, compared to the other sites this site is more impacted through animal husbandry as sheep grazing occurs approx. since 1800 but with lower intensity since 1930.

The reason of the homogeneous vertical distribution of chemical elements in moraine profiles, rather than the larger variations observed in colluvium profiles (see Fig. 5), is the lack of horizon differentiation in the Leptosols developed on till material. The variations in the depth distribution of SOC and sand contents are related with the vertical distribution of the elements and are responsible of the contrasts seen between profiles. Furthermore, the geochemical variability found in the study profiles is linked with the parent materials and their mineralogical composition.

The contrasting patterns between the vertical distribution of the mass activities of ^{137}Cs and ^{210}Pb$_{ex}$ in the moraine and colluvium profiles are likely related to the different periods of ice-retreat. Even for shorter periods as in the case of moraine profiles differences seen between the study profiles might be related to the age of ice-retreat as the lower FRNs contents in PB1 that is the less developed soil since the site became ice-free at ca. AD 1930 might suggest by comparing with PB2 that became ice-free earlier at about AD 1800. Furthermore, the absence of the typical decay pattern of the FRNs mass activities with depth in moraine profiles could be due to several reasons. The till material, the lack of horizon differentiation, and the predominance of coarse fractions in the soil matrix of the moraines may have favoured the rapid infiltration of water carrying the FRNs to deeper layers. In spite that some types of clays may be more efficient in the adsorption of the radionuclides (e.g. Staunton and Roubaud, 1997) specially in the frayed edge sites (Sawhney, 1972), the fixation of the FRNs by the organic matter that may inhibit that of clays is an efficient non specific mechanism fixing ^{137}Cs and

$^{210}Pb_{ex}$ (Takenaka et al., 1998; Gaspar and Navas, 2013; Gaspar et al., 2013). Therefore, the very low content of SOC in the moraine profiles would also contribute to the low fixation of the FRNs. Other reason may be the cryogenic processes and the disturbance of soil by the ice action, which in the moraine sites can be more intense than in the colluviums. Meanwhile, the high values of ^{137}Cs mass activity in the topsoil of the exponential decay profiles in colluvium soils is likely because of the influence of the Chernobyl accident in 1986 (Gjelsvik and Steinnes, 2013).

In relation to the depth distributions of ERNs, the larger variability of ^{226}Ra and ^{232}Th in this environment can be explained by the lack of carbonates as opposed to the observed in Mediterranean carbonate rich soils where high carbonate contents restricted the mobility of these radionuclides (Navas et al., 2002a, b). The depleted levels of ^{40}K at the topsoil of PB1 are related to lower contents in clay and silt fractions. As it is widely known in the literature, (e.g. VandenBygaart and Protz, 1995) the environmental radionuclides are associated with clay minerals or they are fixed within the lattice structure. The significantly higher values of ^{40}K in the profiles of Bødalen are likely related to differences in mineralogical composition, which can be further confirmed by its sharp depletion in the rich organic layer of PE2. Baeza et al. (1995) indicate that radioactivity increases as particle size decreases. In Antarctica profiles increases in clay contents were paralleled with ERNs enrichments (Navas et al., 2005a). In general, bedrock composition appears to be the main factor of variation of the ERNs in the study profiles.

The disequilibrium in the uranium and thorium series can be due to the active hillslope processes such as intense outwash processes and rockfall. Besides, differential mobility of the radionuclides (e.g. Collerson et al., 1991) may have also an influence. Harmsen and de Haan (1980) indicate that U and Th form hydrated cations (UO_2^{2+}, Th^{4+}) that are easily mobilized over a broad range of soil pH.

In spite of differences with the climatic conditions existing in the Southern circumpolar region processes of soil formation similar as those operating in extreme cold regions (Bockheim and McLeod, 2006), can be expected to affect the areas recently deglaciated in the upper Erdalen and Bødalen valleys. Thus, in the LIA moraines and especially in the areas that became ice-free in the past century the role of freeze-thaw, wetting and drying cycles seems to be more important than other weathering mechanisms. In cold regions as in Antarctica freeze-thaw weathering is generally recognized to be the most important process causing rock disintegration and soil formation (Serrano et al., 1996; Hall, 1997; Navas et al., 2008). However, in the areas outside the LIA influence where the colluvium profiles are located physical processes, as rockfall, glaciofluvial and outwash processes and chemical weathering are main soil forming processes.

5 Conclusions

Radionuclide activities in the soils differed as a function of the characteristics of geomorphic elements and the processes occurring on the different geomorphic elements and substrates that have became ice free at different ages. The higher horizon differentiation in the more evolved Regosols developed on colluvium, by comparison with the Leptosols on the moraines determine the larger variability in the elemental composition down the Regosol profiles.

In cold regions as the one of this study information on the period of ice retreat could be derived by the pattern distribution of FRNs, as the typical decay pattern of the FRNs mass activities with depth is not found in moraine profiles of the LIA age compared to the typical decay patterns found in more evolved soils of the colluviums that were deglaciated around 1000 BP. In addition other soil properties can be combined to discriminate main geomorphic processes related to the ice age retreat.

The distribution of ENRs is linked to the mineral composition of the parent materials. Geomorphic and soil processes that trigger the enrichment of the fine fractions containing sheet silicates determine the abundance of ^{40}K and ^{232}Th, whereas ^{238}U and ^{226}Ra are rather associated to minerals included in coarser fractions.

In this environment the transference of the radionuclides and elements down the profile might be time restricted to the periods in which water circulates down the soil profile, which can further influence the differences in soil processes found between colluvium and moraine profiles.

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References

Appleby, P. G. and Oldfield, F.: Application of lead-210 to sedimentation studies, in: Uranium-Series Disequilibrium: Applications to Earth, Marine, and Environmental Sciences, edited by: Ivanovich, J. and Harman, R. S., Clarendon Press, Oxford, UK, 731–738, 1992.

Baeza, A., del Río, M., Jiménez, A., Miró, C., and Paniagua, J.: Influence of geology and soil particle size on the surface-area/volume activity ratio for natural radionuclides, J. Radioanal. Nucl. Ch., 189, 289–299, 1995.

Beylich, A. A. and Laute, K.: Spatial variations of surface water chemistry and chemical denudation in the Erdalen drainage basin, western Norway, Geomorphology, 167–168, 77–90, 2012.

Bickerton, R. W. and Matthews, J. A.: Little Ice Age variations of outlet glaciers from the Jostedalsbreen ice-cap, southern Norway: a regional lichenometric-dating study of ice-marginal moraine sequences and their climatic significance, J. Quaternary Sci., 8, 45–66, 1993.

Bockheim, J. G. and McLeod, J. G.: Soil formation in Wright Valley, Antarctica since the late Neogene, Geoderma, 137, 109–116, 2006.

Collerson, K. D., Gregor, D. J., McNaughton, D., and Baweja, A. S.: Effect of coal dewatering and coal use on the water quality of the East Poplar River, Saskatchewan. A literature review. Inland Waters Directorate, Environment Canada, Scientific Series, No. 177, 1991.

Evans, C. V., Morton, L. S., and Harbottle, G.: Pedologic assessment of radionuclide distributions: use of a radio-pedogenic index, Soil Sci. Soc. Am. J., 61, 1440–1449, 1997.

Fairbridge, R. W.: The encyclopedia of geochemistry and environmental sciences, edited by: Van Nostrand, R., Van Nostrand Reinhold Co, New York, vol. 4A, 1215–1228, 1972.

Gaspar, L. and Navas, A.: Vertical and lateral distributions of ^{137}Cs in cultivated and uncultivated soils on Mediterranean hillslopes, Geoderma, 207–208, 131–143, 2013.

Gaspar, L., Navas, A., Machín, J., and Walling, D. E.: Using ^{210}Pb$_{ex}$ measurements to quantify soil redistribution along two complex toposequences in Mediterranean agroecosystems, northern Spain, Soil Till. Res., 130, 81–90, 2013.

Gjelsvik, R. and Steinnes, E.: Geographical trends in ^{137}Cs fallout from the Chernobyl accident and leaching from natural surface soil in Norway, J. Environ. Radioactiv., 126C, 99–103, 2013.

Hall, K.: Rock temperatures and implications for cold region weathering. I: New data from Viking Valley, Alexander Island, Antactica, in: Permafrost Periglac. Proc., vol. 8, 69–90, 1997.

Harmsen, K. and de Haan, F. A, M.: Occurrence and behavior of uranium and thorium in soil and water, Neth. J. Agr. Sci., 28, 40–62, 1980.

Laute, K. and Beylich, A. A.: Influences of the Little Ice Age glacier advance on hillslope morphometry and development in paraglacial valley systems around the Jostedalsbreen ice cap in Western Norway, Geomorphology, 167–168, 51–69, 2012.

Laute, K. and Beylich, A. A.: Holocene hillslope development in glacially formed valley systems in Nordfjord, western Norway, Geomorphology, 188, 12–30, 2013.

Laute, K. and Beylich, A. A.: Morphometric and meteorological controls on recent snow avalanche distribution and activity at hillslopes in steep mountain valleys in western Norway, Geomorphology, in press, doi:10.1016/j.geomorph.2013.06.006, 2013.

Lopez-Capel, E., Krull, E. S., Bol, R., and Manning, D. A. C.: Influence of recent vegetation on labile and recalcitrant carbon soil pools in central Queensland, Australia: evidence from thermal analysis quadrupole mass spectrometry-isotope ratio mass spectrometry, Rapid Commun. Mass Sp., 22, 1751–1758, 2008.

Lutro, O. and Tveten, E.: Bedrock map ÅRDAL M 1 : 250.000. Norges geologiske undersøkelse, Trondheim, 1996.

Matthews, J. A., Shakesby, R. A., Schnabel, C., and Freeman, S.: Cosmogenic ^{10}Be and ^{26}Al ages of Holocene moraines in southern Norway I: testing the method of confirmation of the date of the Erdalen event (c. 10 ka) at its type site, Holocene, 18, 1155–1164, 2008.

Navas, A., Soto, J., and Machín, J.: Edaphic and physiographic factors affecting the distribution of natural gamma-emitting radionuclides in the soils of the Arnás catchment in the Central Spanish Pyrenees, Eur. J. Soil Sci., 53, 629–638, 2002a.

Navas, A., Soto, J., and Machín, J.: ^{238}U, ^{226}Ra, ^{210}Pb, ^{232}Th and ^{40}K activities in soil profiles of the Flysch sector (Central Spanish Pyrenees), Appl. Radiat. Isotopes, 57, 579–589, 2002b.

Navas, A., Soto, J., and López-Martínez, J.: Radionuclides in soils of Byers Peninsula, South Shetland Islands, Western Antarctica, Appl. Radiat. Isotopes, 62, 809–816, 2005a.

Navas, A., Soto, J., and Machín, J.: Mobility of natural radionuclides and selected major and trace elements along a soil toposequence in the central Spanish Pyrenees, Soil Sci., 170, 743–757, 2005b.

Navas, A., López-Martinez, J., Casas, J., Machín, J., Durán, J. J., Serrano, E., Cuchí, J. A., and Mink, S.: Soil characteristics on varying lithological substrates in the South Shetland Islands, maritime Antarctica, Geoderma, 144, 123–139, 2008.

Nesje, A.: Kvartærgeologiske undersøkningar i Erdalen, Stryn, Sogn og Fjordane, M. Sc. thesis, University of Bergen, 201 pp., 1984.

Sawhney, B. L.: Selective adsorption and fixation of cations by clay minerals: a review, Clay. Clay Miner., 20, 93–100, 1972.

Serrano, E., Martínez de Pisón, E., and López-Martínez, J.: Periglacial and nival landforms and deposits, in: Geomorphological Map of Byers Peninsula, Livingston Island, edited by: López-Martínez, J., Thomson, M. R. A., and Thomson, J. W. BAS Geomap Series 5-A, British Ant Surv, Cambridge, 15–19, 1996.

Serrano, E. and López-Martínez, J.: Rock glaciers in the South Shetland Islands, Western Antarctica, Geomorphology, 35, 145–162, 2000.

Staunton, S. and Roubaud, M.: Adsorption of ^{137}Cs on montmorillonite and illite: effect of charge compensanting cation, ionic strength, concentration of Cs, K and fulvic acid, Clay. Clay Miner., 45, 251–260, 1997.

Takenaka, C., Onda, Y., and Hamajima, Y.: Distribution of cesium 137 in Japanese forest soils: correlation with the contents of organic carbon, Sci. Total Environ., 222, 193–199, 1998.

Van Cleef, D. J.: Determination of ^{226}Ra in soil using ^{214}Pb and ^{214}Bi inmediately after sampling, Health Phys., 67, 288–289, 1994.

VandenBygaart, A. J. and Protz, R.: Gamma radioactivity on a chronosequence, Pinery Provincial Park, Ontario, Can. J. Soil Sci., 75, 73–84, 1995.

Winkler, S., Elvehøy, H., and Nesje, A.: 2009: Glacier fluctuations of the Jostedalsbreen, western Norway, during the past 20 years: the sensitive response of maritime mountain glaciers, Holocene, 19, 395–414, 2009.

Table 1. Physiographic and climatic characteristics of the drainage basins of Erdalen and Bødalen (Nordfjord region, Norway).

	Erdalen	Bødalen
Geographical coordinates	61°50′ N, 07°10′ E	61°48′ N, 07°05′ E
Drainage basin area [km^2]	79.5	60.1
Elevation min [m a.s.l.]	20	52
Elevation max [m a.s.l.]	1888	2083
Relief [m]	1868	2031
Mean slope [°]	32	34
Lithology	Precambrian granitic orthogneisses	
Dominant soils	Leptosols, Regosols	
Vegetation	Birch, grey alder, grass, moos, lichens	
Annual precipitation [mm] (at 360 m a.s.l.)	1500	1500
Mean annual air temperature [°C] (at 360 m a.s.l.)	5.5	5.5
Surface area percentages[a] [%]		
Glacier	18	38
Bedrock	45	43
Slope deposits/regolith	32	16
Valley infill	5	2
Lake	< 1	1

[a] As % of the total drainage basin surface area.

Table 2. Summary statistics of main properties in the soil samples on moraines and colluvium. Different letters indicate significant differences at the p level 0.05 between moraines and colluvium soils.

	Moraines $n = 9$					Colluvium $n = 12$				
	Mean		SD	Min	Max	Mean		SD	Min	Max
SOC %	0.48	a	0.44	0.03	1.03	3.18	a	3.82	0.43	14.39
ACF %	0.28	a	0.31	0.03	0.79	2.78	a	3.40	0.38	12.69
SCF %	0.07	a	0.05	0.01	0.12	0.36	a	0.31	0.03	1.10
pH	5.45	b	0.33	5.02	5.85	4.80	a	0.24	4.45	5.16
2000–50 µm %	72.58	a	21.84	42.40	95.00	60.28	a	23.52	13.50	81.60
50–2 µm %	23.86	a	18.51	4.60	49.20	36.22	a	20.36	17.40	75.70
< 2 µm %	3.52	a	3.36	0.40	8.40	3.51	a	3.21	1.00	10.80

SD: Standard deviation, CV: Coefficient of variation.

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Table 3. Summary statistics of radionuclide contents in the samples of the soil profiles of the moraines and colluvium. Different letters indicate significant differences at the *p* level 0.05 between moraines and colluvium soils.

$\mathrm{Bq\,kg^{-1}}$	Moraines $n = 9$					Colluvium $n = 12$				
	Mean		SD	Min	Max	Mean		SD	Min	Max
^{137}Cs	34.63	a	36.96	2.33	85.10	63.38	a	117.55	1.23	346.00
^{210}Pb$_{ex}$	2.63	a	5.26	b.d.l.	13.00	17.93	a	36.64	b.d.l.	102.40
^{40}K	1177.78	b	142.02	820.00	1320.00	890.42	a	124.45	652.00	1070.00
^{226}Ra	36.84	b	6.68	24.60	47.70	18.68	a	6.87	12.60	30.70
^{232}Th	56.97	b	13.91	33.70	83.70	39.27	a	13.86	12.60	61.20
^{238}U	52.22	b	7.65	41.50	64.90	38.99	a	6.46	28.10	47.10
^{210}Pb	25.82	a	12.74	3.91	45.40	29.65	a	43.13	b.d.l.	118.00

SD: Standard deviation, CV: Coefficient of variation, b.d.l.: below detection limit.

Table 4. Summary statistics of the elemental composition (mg kg^{-1}) in the samples of the soil profiles of the moraines and colluvium. Different letters indicate significant differences at the p level 0.05 between moraines and colluvium soils.

	Moraines $n = 9$					Colluvium $n = 12$				
	Mean		SD	Min	Max	Mean		SD	Min	Max
Be	1.5	b	0.0	1.4	1.5	1.1	a	0.1	0.8	1.3
Mo	0.5	a	0.2	b.d.l.	0.7	0.8	b	0.1	0.6	1.0
Sb	1.4	a	0.3	0.9	1.8	3.1	b	1.1	1.6	5.1
Li	7.6	a	1.0	5.2	8.5	9.0	a	6.0	0.8	17.4
Bi	21.6	a	1.6	18.6	23.8	24.4	a	7.2	12.1	34.2
Cu	17.3	a	10.5	7.1	41.2	22.7	a	13.2	5.6	47.3
Pb	31.0	b	1.0	29.5	32.6	26.6	a	3.6	19.3	31.8
Tl	24.6	a	3.4	19.2	29.7	49.6	b	26.0	13.0	86.4
V	34.9	a	4.9	25.9	40.3	69.1	b	21.3	32.8	99.3
Zn	29.8	a	2.5	23.9	33.1	58.9	b	34.8	9.6	110.0
Ni	27.0	a	2.9	22.4	31.4	55.6	b	37.7	14.0	121.0
Cr	25.1	a	4.6	17.1	30.5	139.0	b	99.0	30.6	323.9
Sr	241.9	a	16.3	212.7	261.1	306.2	a	94.3	172.1	465.5
S	125.1	a	37.2	90.8	216.2	371.3	b	232.9	191.5	1005.0
Mn	275.3	a	40.2	211.7	336.7	571.7	b	349.3	117.5	1088.0
P	839.3	a	109.3	613.6	942.8	1239.9	b	356.0	545.4	1791.0
B	3197.8	b	237.5	2970.0	3770.0	1010.1	a	796.4	300.7	3090.0
Ti	3092.2	a	419.0	2240.0	3840.0	4580.0	b	1070.0	2720.0	6500.0
Mg	2710.8	a	610.1	1771.0	3633.0	11 086.1	b	8748.6	1206.0	25 100.0
Ca	8241.4	a	778.3	6516.0	8982.0	12 180.0	b	2496.8	6728.0	16 140.0
K	28 358.9	b	1423.5	26 140.0	30 120.0	20 246.7	a	3394.7	12 810.0	24 980.0
Na	30 607.8	b	1579.4	29 000.0	33 940.0	21 153.3	a	4763.4	13 520.0	27 270.0
Fe	19 300.0	a	2500.9	15 490.0	22 960.0	33 838.4	b	15 949.9	9471.0	56 000.0
Al	45 526.7	a	4215.0	40 330.0	53 590.0	48 230.0	a	10 710.9	27 050.0	61 550.0

SD: Standard deviation, b.d.l.: below detection limit.

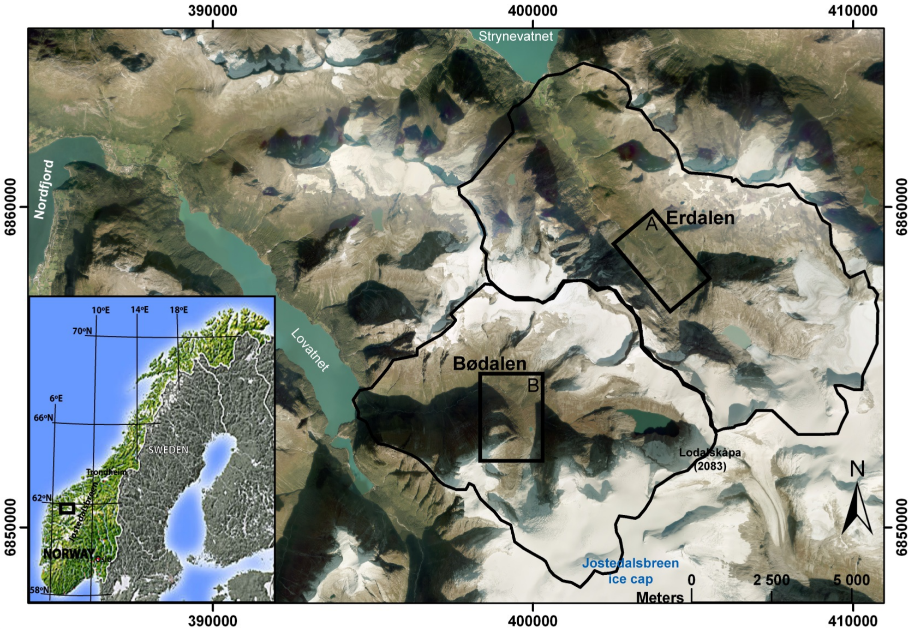

Fig. 1. Location of the Nordfjord region (western Norway), aerial photograph of the Erdalen and Bødalen glacial valleys and situation of the study areas.

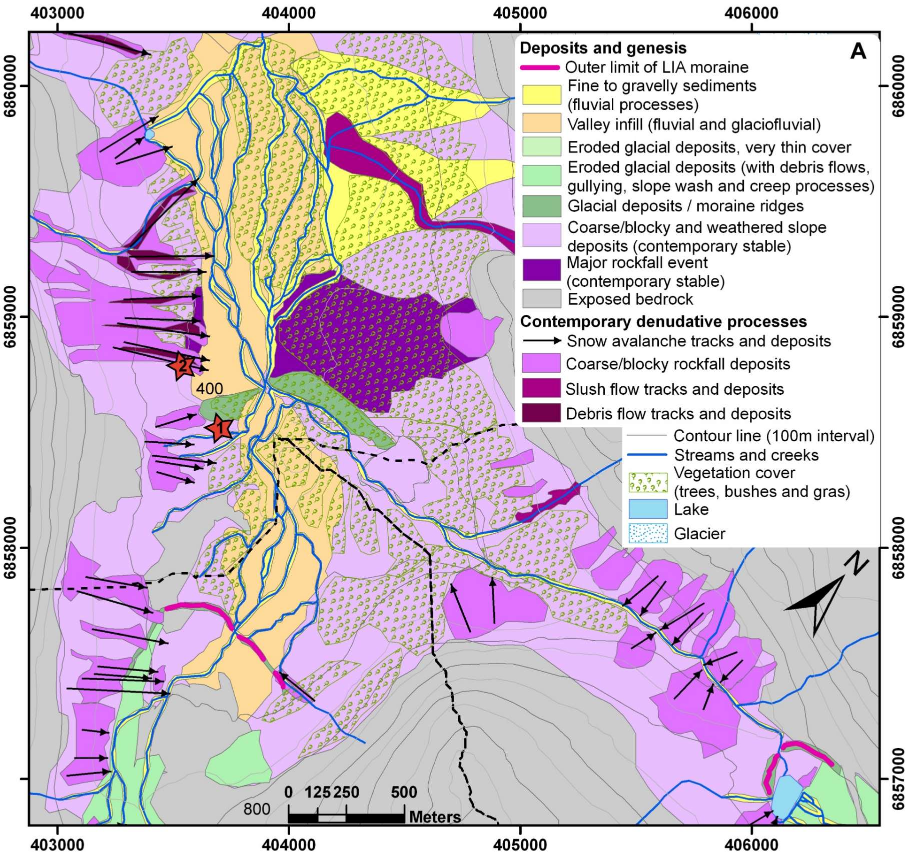

Fig. 2. Geomorphological map of the Erdalen drainage basin (modified after Laute and Beylich, 2012) and location of the study profiles (1) PE1 and (2) PE2.

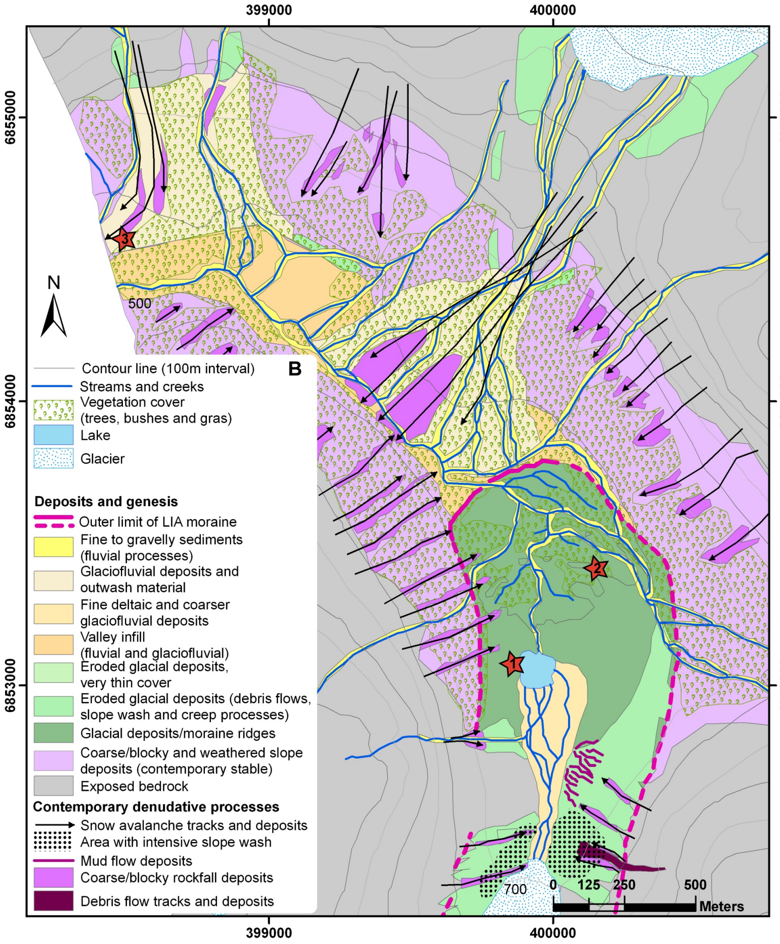

Fig. 3. Geomorphological map of the Bødalen drainage basin (modified after Laute and Beylich, 2012) and location of the study profiles (1) PB1, (2) PB2 and (3) PB3.

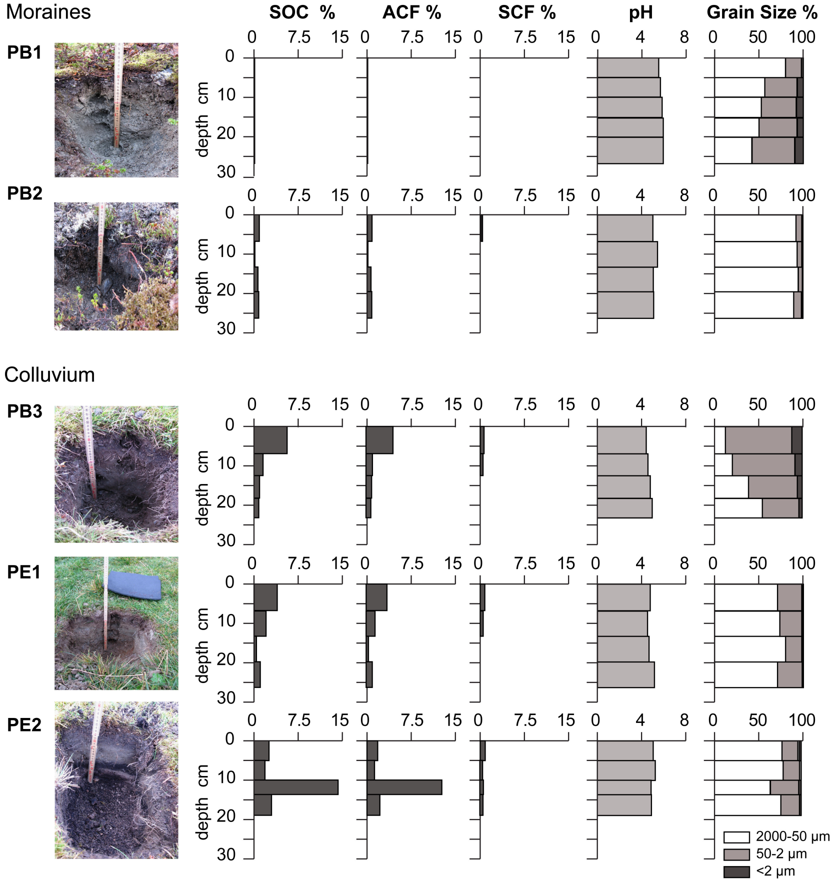

Fig. 4. The study profiles on the Leptosols of the moraines and the Regosols of the colluvium and the depth distribution of main soil properties.

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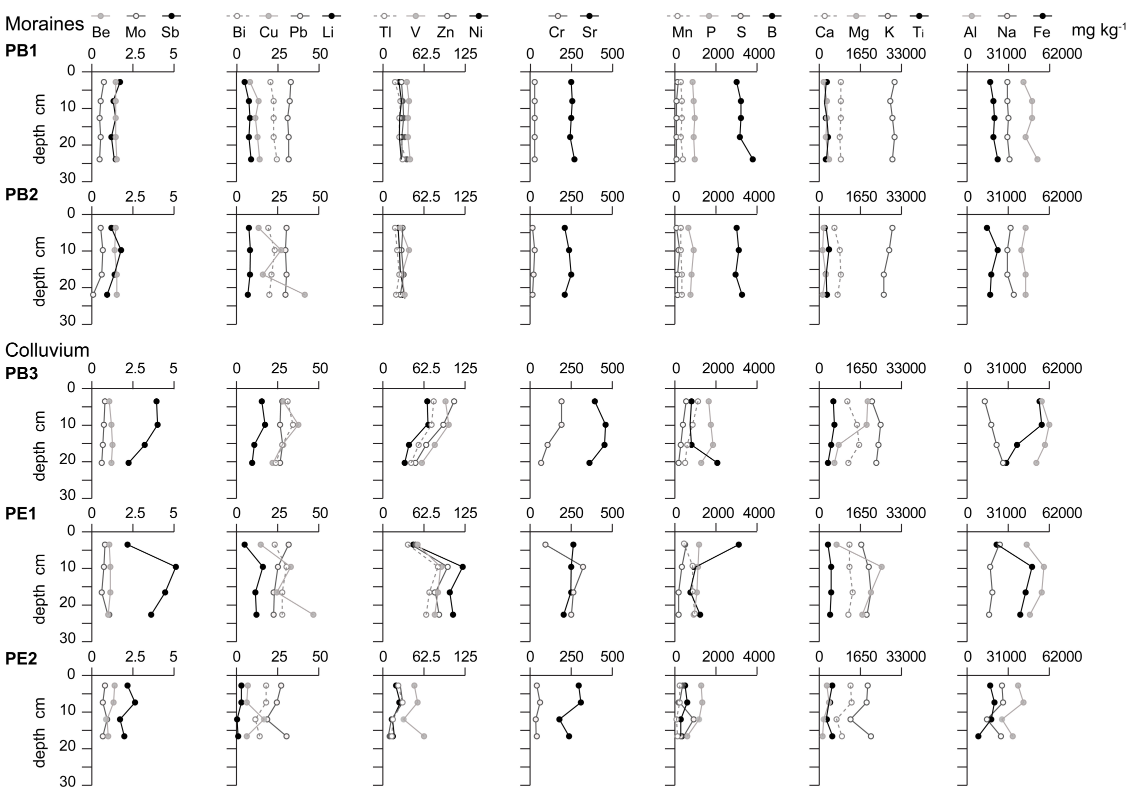

Fig. 5. Vertical distribution of the chemical elements (mg kg^{-1}) in the soil profiles on the moraines and colluvium.

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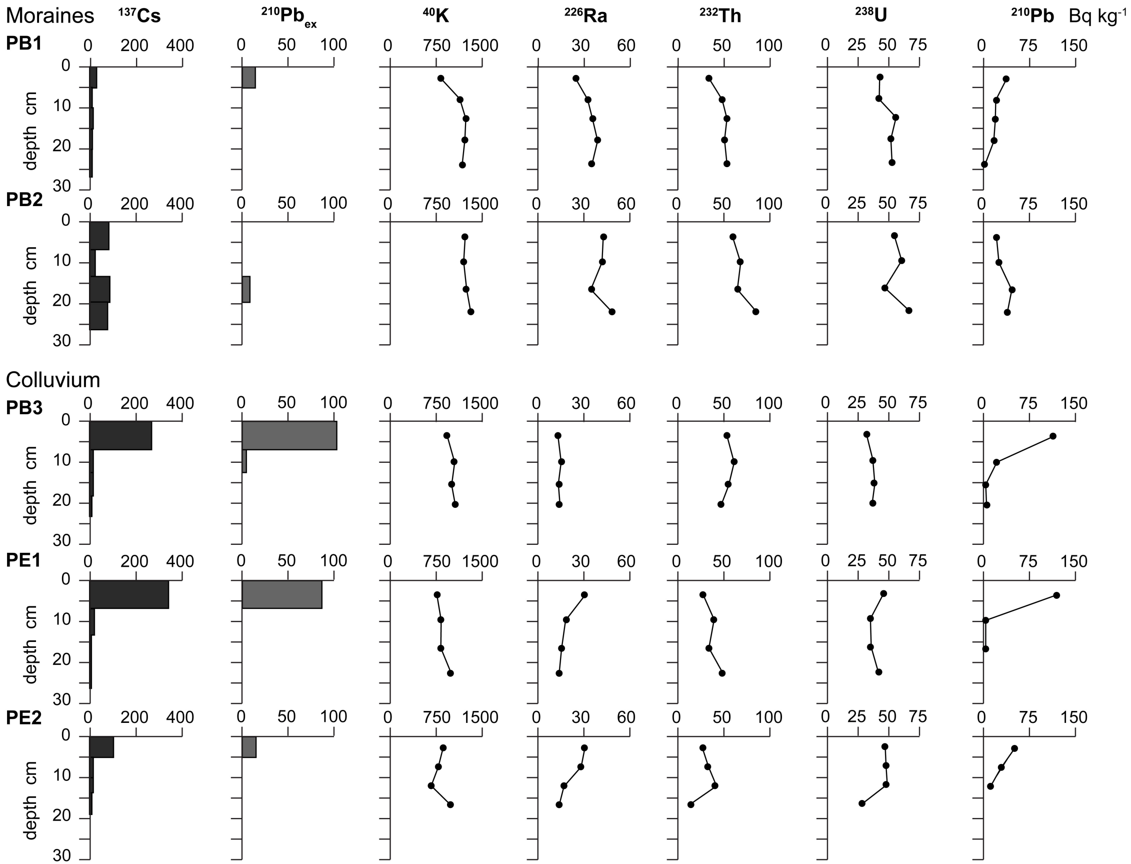

Fig. 6. Depth distribution of the mass activities (Bq kg^{-1}) of FRNs and ERNs in the soil profiles on the moraines and colluvium.