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Radionuclides and soil properties as indicators of glacier retreat in a recently deglaciated permafrost environment of the Maritime Antarctica

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Abstract

Many ice-free environments in Maritime Antarctica are undergoing rapid and substantial environmental changes in response to recent climate trends. This is the case of Elephant Point (Livingston Island, South Shetland Islands, SSI), where the glacier retreat recorded during the last six decades exposed 17% of this small peninsula, namely a moraine extending from the western to the eastern coastlines and a relatively flat proglacial surface. In the southern margin of the peninsula, a sequence of Holocene raised beaches and several bedrock plateaus are also distributed. A main issue in this environment is the role of glacier retreat and permafrost controlling the recently formed soils. To this purpose, a total of 10 sites were sampled along a transect crossing raised beaches and moraine materials following the direction of glacier retreat. At the selected sites surface samples were collected until 12 cm depth and sectioned at 3 cm depth intervals to analyse main properties, grain size, pH, electrical conductivity and carbonates. Besides, elemental composition and fallout (FRNs) and environmental radionuclides (ERNs) were analysed. To assess if profile characteristics within the active layer are affected by glacier retreat variations of organic carbon and carbon fractions and ^{137}Cs contents were examined. The presence of organic carbon (range: 0.13–3.19 %), and ^{137}Cs (range: bdl–10.1 Bq kg^{-1}) was only found at the raised beaches. The surface samples had abundant coarse fractions in rich sandy matrix with increasing acidic pH towards the coast. Significant differences were found in the elemental composition and FRNs and ERNs between the moraine and raised beaches. Soil forming processes are related to the time of exposure of the landforms after glacier retreat. The results obtained confirm the potential for using geomorphological, edaphic and geochemical data to assess the influence of different stages of glacier retreat in recent soils and sediments.

Key words: ^{137}Cs; SOC; ERNs; Cryosols; glacial landforms; Elephant Point.

1. Introduction

Recently deglaciated environments in Maritime Antarctica are affected by very intense paraglacial dynamics in the form of a wide range of periglacial, alluvial and slope processes (Oliva and Ruiz-Fernández, 2015). Terrestrial ecosystem dynamics in these areas is therefore constrained by this geomorphic setting as well as by climate conditions in an area that has undergone significant climate oscillations over the last decades (Turner et al., 2005, 2016; Oliva et al., 2017a).

The Maritime Antarctica region, including offshore islands, presents generally warmer and wetter climate conditions than the interior of the continent, which favours an intense geochemical weathering of the substrate and relatively rapid soil formation (Campbell and Claridge, 1987). Both high moisture conditions and warmer temperatures are main key factors controlling soil development in the region (Bockheim, 2014). Small changes in the thermal and moisture regimes may affect soil formation processes, as it has been reported in other cold-climate environments (Oliva et al., 2014). Soil forming processes are also strongly influenced by the interaction between permafrost and Geomorphology, such as cryoturbation processes that are widespread in ice-free regions in Maritime Antarctica generating patterned ground soils (López-Martínez et al., 2012; Ruiz-Fernández and Oliva, 2016). Also, mechanical disintegration plays a key role in soil development through freeze-thaw activity. This process promotes frost shattering of the bedrock and Quaternary sediments, enhancing the potential of chemical weathering on soil formation (Navas et al., 2008).

Biological activity is another factor influencing soil processes in the Maritime Antarctica affecting the physical and chemical properties as well as the thermal regime of the active layer (Guglielmin et al., 2008). Ornithogenic soils, mainly resulting from bird and penguin activity, have been defined as the most well developed soils in Maritime Antarctica (Moura et al., 2012; Pereira, et al., 2013).

Recent studies suggest that climate warming in Maritime Antarctica may affect the length of the growing season (Hartley et al., 2010; Bockheim et al., 2013), thus the subsequent expansion of the plant cover may favour weathering together with the mobility of chemical elements and nutrients in soils (e.g. Otero et al., 2013). These future climate scenarios may also affect plant and microbial activity, which may promote the dissolution and mobilization of soil nutrients (Quayle et al., 2002).

The western fringe of Livingston Island (South Shetland Islands; SSI) concentrates several ice-free regions, one of which is the study area of this research. Elephant Point is a tiny ice-free environment in Livingston Island encompassing the most representative geomorphological processes and landforms characteristic of the northern Antarctic Peninsula (Oliva and Ruiz-Fernández, 2016), as well as the best preserved archaeological sites in the Maritime Antarctica. Based on these natural and historical heritage, it has been recently proposed to be designated an Antarctic Special Protected Area (Oliva et al., 2016b).

Close to Elephant Point, there is Byers Peninsula, one of the most studied ice-free areas in the Maritime Antarctica (Benayas et al., 2013). It is the largest deglaciated environment in the SSI and one of the vastest in the western Antarctic Peninsula (Mink et al., 2013). The distribution of permafrost in this peninsula can be used as a reference for Elephant Point; it is supposed to be continuous in the central plateau at elevations between 40 and 90 m a.s.l., with the depth of the active layer variable oscillating between 85 cm and slightly more than 1 m (Hall, 1993; Serrano et al., 2008; Otero et al., 2013; de Pablo et al., 2013, 2014; Oliva et al., 2017b; Correia et al., 2017).

However, despite accelerated changes in terrestrial ecosystem dynamics affecting soil formation – such as permafrost degradation and changes in active layer thickness –, surface soil characteristics and processes in the recently deglaciated environments of western Livingston Island have not yet been examined in detail. With the purpose of filling this gap, a total of 10 sites were selected to collect surface samples along a transect crossing different geomorphological units following the direction of ice retreat to assess if the surface profile characteristics are affected by glacier retreat. This study aims to give answer to the following specific objectives: i) assess if fallout radionuclides (^{137}Cs), organic carbon and carbon fractions and geochemistry can be used as tracers of glacier retreat in recently deglaciated areas; ii) examine the dependence of soil development on glacier retreat; iii) examine the relationship between permafrost distribution, geomorphologic units and surface processes and iv) evaluate the role of time in soil formation in recently deglaciated environments in the Maritime Antarctica.

2. Material and methods

2.1 Study area

The SSI are located in the NW fringe of the Antarctic Peninsula region. Livingston Island is located in the western SSI, and Elephant Point sits in the SW corner of this island (Fig. 1). This small ice-free area (1.16 km^2) appeared following the Holocene retreat of the cold-based Rotch Dome glacier in its distal area (Oliva and Ruiz-

Fernández, 2015), which exposed an ice-rich permafrost moraine extending from the E to the W of the peninsula. The northern slope of the moraine is now affected by intense periglacial slope processes related to paraglacial dynamics, whereas the southern slope is much more stable due to the fact that is no longer influenced by paraglacial activity (Oliva and Ruiz-Fernández, 2015). The lowest areas are composed of a succession of raised beaches and the present-day beach. The main geomorphological units and landforms, the characteristics of underlying materials and the location of the study samples are shown in the map included in Figure 2.

Climate in the SSI is typical of polar maritime environments. The mean annual temperature in the nearby Byers Peninsula was -2.8 °C (2002-2010) at 70 m a.s.l. with a total precipitation ranging from 500 to 800 mm (Bañón et al., 2013). These climate conditions favour intense physical weathering, particularly during summer when freeze-thaw cycles in the ground are more frequent.

Elephant Point is composed of weathered basalts, schists with granodiorites and shales distributed across the moraine sediments (Oliva and Ruiz-Fernández, 2016). These sediments are being intensely affected by physical weathering processes. Landforms, deposits and active processes are typical of the Maritime Antarctica, with periglacial processes being widespread in this ice-free environment. The raised beaches also show development of mudboils, stone fields and patterned ground features showing evidence of cryoturbation activity related to seasonal freezing. Frozen ground conditions are widespread in the area, possibly associated to a permafrost regime with an active layer thickness between 47 and 65 cm in January 2014, except in the marine terraces where frozen ground was not detected (Oliva and Ruiz-Fernández, 2016).

Vegetation is very scarce and mainly consists of mosses and lichens mostly distributed on the bedrock plateaus and raised beaches where biological activity is more intense. Two grass species (*Deschampsia antarctica* and *Colobanthus quitensis*) are distributed in some protected sites across the flat raised beaches (Ruiz-Fernández et al., 2017). The soils (Cryosols) are shallow and generally poorly developed; with almost not horizon differentiation. The presence of organic-rich layers is only found near bird colonies. In Elephant Point there are five rockeries of gentoo penguins (*Pygoscelis papua*) and seven colonies of elephant seals (*Mirounga leonina*), mainly on the raised beaches. In addition, there are numerous colonies of southern giant petrels (*Macronectes giganteus*) in the bedrock plateaus (Ruiz-Fernández et al., 2017).

The bedrock plateaus and the highest raised beaches were the firstly deglaciated areas in the peninsula becoming exposed before the development of the moraine. The moraine is a polygenetic formation composed of several arches formed by accumulation of glacigenic material deposited after each glacial expansion that was originated since ca. 1800 cal yr BP (Oliva and Ruiz-Fernández, 2016). The most recent internal sediment accumulation was recently exposed by the retreat of the Rotch Dome glacier (Fig. 1). The external part of the moraine can be ascribed to ca. 1800 cal yr BP based on the fact that in the nearby Byers Peninsula the same moraine system overlays raised beaches dated of that age (Hansom, 1979; Hall and Perry, 2004). Furthermore, the dating of the bottom sediments of a sediment core in Byers Peninsula at scarce 500 m from the moraine also reported a similar age (Oliva et al., 2016a), confirming therefore a Late Holocene age.

The raised beaches and moraine present very distinctive features. On the raised beaches mosses and cushions of *Deschampsia antartica* cover the soils together with abundant rounded pebbles. The presence of fauna - namely bird colonies (penguins and petrels) and mammals (seals) - contribute to the organic enrichment of the soils of the raised beaches and present-day beach (Ruiz-Fernández et al., 2017). The sediments of the moraine are coarse and loose angular gravels, pebbles and rock fragments embedded in a sandy matrix. The moraine has no vegetation cover except few incipient mosses and isolated specimens of *Deschampsia antarctica* at the foot of the most external ridge of the moraine.

2.2. Selection of sampling sites and sample collection

For this study, the selection of the sampling sites pursued to assess the influence of glacier retreat on soil formation on the different geomorphological units affected by glacier retreat. Field sampling was carried out in late January 2014, after a snowy winter in the SSI, which conditioned a late thawing of the active layer of the permafrost and seasonal frost in non-permafrost sites.

A total of ten sites corresponding to soils and sediments developed on raised beaches and glacial deposits were selected. Pits were excavated to collect the upper part representing different stages of ice retreat. Surface soil and sediment sections were examined following the deglaciation from the coastline to the present-day glacier front along the transect drawn in Figure 2. Five surface profiles were established on the raised beaches (EP1-EP5) and the other five were established on the moraine (EP6-EP10) (Table 1). The uppermost 12 cm of these sections were sampled using 7 cm diameter PVC tubes. Samples were maintained refrigerated in the sealed PVC cores until they were examined at the laboratory. Each sample was sectioned at 3 cm depth intervals obtaining 4 subsamples per site.

2.3. Laboratoy analysis

Samples were dried, ground, homogenized and quartered. Each sample was sieved at 2 mm and the grain size fraction > 2 mm containing gravels, stones and rock fragments was separated from the fine fraction (< 2 mm) and weighted to estimate the percentage of the coarse fraction. Main soil properties, radionuclides and elemental composition were analysed in the fraction < 2 mm. The pH (1:2.5, soil: water), electrical conductivity and carbonate contents were measured in the 12 cm bulk samples, while the rest of analyses were performed in the 3 cm interval samples. The presence of carbonates was tested with diluted 1M HCl.

Soil texture was established after analysis of the clay, silt and sand contents. Analyses were performed using laser diffraction particle size analyser, after eliminating the organic matter with H2O2 (10%) heated at 80 ºC. Disaggregation of the samples was done with sodium hexametaphosphate (40%) by stirring for 2 h. Further dispersion of the samples was done by applying ultrasound for few minutes.

The contents of soil organic carbon (SOC) and of the active (ACF) and stable (SCF) carbon fractions were estimated through the dry combustion method. The soil organic carbon (SOC %) at 310º (active carbon fraction, ACF) and at 550º (stable carbon fraction, SCF) were analysed by using a LECO RC-612 multiphase carbon analyser (LECO Corporation, St. Joseph, MI, USA) designed to differentiate forms of carbon by oxidation temperature. The most thermally labile components of SOC, the active and decomposable fraction (ACF), are released at 300-350 ºC while decomposition of the more refractory and stable carbon (SCF) occurs at around 420-550 ºC (López-Capel et al., 2008).

The analyses of the following stable elements: Lithium (Li), Potassium (K), Sodium (Na) (alkaline), Beryllium (Be), Magnesium (Mg), Calcium (Ca), Strontium (Sr) (light metals), Chromium (Cr), Cupper (Cu), Manganese (Mn), Iron (Fe), Aluminium (Al), Zinc (Zn), Nickel (Ni), Cobalt (Co), Cadmium (Cd), Thallium (Tl), Bismuth (Bi), Vanadium (V), Titanium (Ti), Lead (Pb) (heavy metals), Boron (B), Antimony (Sb), Arsenic (As) (metalloids) and Phosphorous (P) Sulphur (S), Molybdenum (Mo) and Selenium (Se) were performed by atomic emission spectrometry using inductively coupled plasma ICP (OES, solid state detector) after total acid digestion with HF (48%) in a microwave oven (Navas and Machín, 2002). Concentrations, obtained after three measurements per element, are expressed in mg/kg.

Gamma emissions of Uranium-238 (^{238}U), Radium-226 (^{226}Ra), Thorium-232 (^{232}Th), Potassium-40 (^{40}K) and Cesium-137 (^{137}Cs) were measured in the interval samples using a Canberra Xtra high resolution, low background, hyperpure germanium coaxial gamma detector coupled to an amplifier and multichannel analyser (Navas et al., 2005a, b). The detector has a relative efficiency of 50% and a resolution of 1.9 keV (shielded to reduce background) and was calibrated using standard certified samples that had the same geometry as the measured samples. Count times over 24 h provided an analytical precision of about ± 3-10% at the 95% level of confidence.

Considering the appropriate corrections for laboratory background, ^{238}U was determined from the 63-keV line of ^{234}Th; ^{226}Ra was determined from the 352-keV line of ^{214}Pb; ^{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. Activities are expressed as Bq kg^{-1} dry soil.

A statistical analysis was applied to assess the statistical significance of the differences in the means of the study parameters using the Least Significant Difference (LSD Fisher) test. Significant differences were considered at a $p<0.05$. Discriminant function analyses were also performed to assess if the radionuclides and elemental composition differentiated the main surface formations in this study, i.e. the moraine from the raised beaches.

3. Results

3.1 Sample characterization

The top 12 cm sampled in Elephant point varied from acidic to almost neutral, with pH ranging from 4.52 to 6.73 (Table 2). The pH values in the raised beach samples were significantly more acidic than in the moraine ($p \leq 0.001$), with values below 5, apart from a value of 6.37 at EP1 (the youngest and lowest raised beach), whereas pH values in the moraine sediments were higher, ranging from 5.97 to 6.73. Electrical conductivity was low and oscillated between 0.049 and 0.388 dSm^{-1} with not specific trend observed in relation with the location of the sites along the transect. Carbonates were not detected in the study samples.

The high stoniness content is a characteristic feature in all sites, but gravels and stones were round in the raised beaches in contrast with those in the moraine that were angular to subangular. The surface soils of the raised beaches had significantly lower clay and silt contents but higher abundance of sand and of the coarsest fractions (>12.5 mm) (Table 3) which was especially abundant at lower layers of EP3 and EP5. However, the coarsest fraction was not as abundant in the moraine samples (Fig. 3). The highest contents of fine particles were found at the top layers of the profiles apart from in EP2 and EP4. The prevailing texture was loamy sand, though sand texture was also frequent in the soils of the raised beaches, where sand contents reached the highest percentages (EP2, EP4, EP5). These soils also had the lowest percentages of the clay fraction (range 0.3 – 4.1 %) with the exception of EP1, whereas in the moraine the content of clay and silt fractions was higher (range 1.7 – 10.7 % and 11.4 – 40.5, respectively).

Concerning the depth distribution of the grain size fractions, the sand fraction was the most abundant in all depth intervals with higher contents in the sections of the raised beaches, apart from EP1. Slight decreases with depth in the clay fraction were observed in most of the moraine profiles (Fig. 3). The > 12.5 mm fraction had variable trends showing marked increases with depth at EP3, EP6 and EP9.

Soil organic carbon and carbon fractions were only found in the soils of the raised beaches (Table 2). The SOC contents were low (range 0.13 - 3.19 %), although SOC was more abundant in the soils of the intermediate raised beaches reaching its highest value at EP3. Labile carbon fractions were the most abundant (ACF range: 0.25 – 2.47 %) in comparison with the more stable ones (SCF range: undetected – 0.717). Thus ACF contents were 3 to 4 times higher than SCF ones at the intermediate raised beaches. The lowest SOC contents were found at EP1, where SCF contents in some layers were negligible. The depth distribution of SOC and the carbon fractions shows that the highest contents occur at the top layer and decreased exponentially with depth (Fig. 4). However, the opposite pattern was observed at EP1 where the highest content was found at the lowest layer. As shown in Figure 4, the sites on the moraine did not have any organic carbon content.

There were significant differences in the means of the study properties in the soils on the raised beaches and the sediments of the moraine apart from the means of EC and fractions < 2mm and 6.3-12.5 mm (Table 3).

3.2 Elemental composition

Figure 5 presents the lateral variation of the study elements. The range of the most abundant major elements (mg kg^{-1}) were 45000-67340 for Fe, 39350-58480 for Al, 24220-38070 for Ca, 14600-22340 for Na, 4855-10060 for Mg, 4630-9880 for Ti, 3993-6815 for K and 1233-3476 for V. Phosphorous was also abundant (range: 563-2270 mg kg^{-1}) especially in the soils of the raised beaches, followed by ranges of 770 to 1152 for Mn, 307-645 for S, 160-269 for Sr and 168-244 for V. The range of minor components (mg kg^{-1}) were 68.1-92.9 for Tl, 46.7-67.4 for Zn, 34.5-65.8 for Cr, 40.1-57.1 for Bi, 16.1-56.4 for Cu, 15.6-28.3 for Pb, 12.8-29.0 for Ni and 5.2-14.1 for Li. As trace elements As and Co were not detected and for the rest of elements the ranges (mg kg^{-1}) were bdl-5.29 for Se, 1.31-3.18 for Rb, bdl-1.59 for Cd, bdl-1.02 for Mo and bdl-0.73 for Be.

As shown in Figure 5 most chemical elements varied little and were considerably more homogeneous in the moraine sections than in the soils of the raised beaches, with the exception of K, Mg, Mn and the trace elements Cu, Cr, Ni, Rb and Mo. In clear contrast the contents of most chemical elements in the soils of the raised beaches exhibited variations from the site of the oldest raised beach (EP5) to the youngest one (EP1). An exception was Na that remained quite homogeneous in all sites. In comparison with the composition of the moraine sediments, the soils of the raised beaches showed decreasing trends in the contents of most elements, namely Al, Ca, Mg, B, Mn, Sr, Tl, Cu, Li, Pb and Mo. But the opposite was found for Fe, Ti, P, V, Bi, Rb and Cd that increased towards the coast. Within the moraine sites, EP10 that is closer to the glacier had the most distinctive elemental composition, whereas within the raised beaches EP1, which is closer to the sea, was the most different.

The vertical distribution of some major elements in Figure 6 shows that Al content was higher in the top 3 cm at EP1, EP8, EP9 and EP10. Iron was less abundant at the topsoil of the raised beaches apart from EP5 but the opposite was found at the sites closer to the glacier front, EP8, EP9 and EP10. The content of P was half in the moraine sediments compared to that in raised beaches where P generally accumulated below the top 3 cm.

The means of major elements in the soils of the raised beaches were significantly different to that in the moraine (Table 4), with the exception of K. Non-significant differences were found for the trace elements Tl, Zn, Cr, Pb, Ni, and Rb (Table 4). In all the moraine sites the mean contents of Ca, B, Cu, Be and Li were higher than in the raised beaches, but the opposite pattern was found for Ti, P, V, Bi and Cd. The results of the Discriminant Function Analysis considering all the study elements (Fig. 7, Table 5) show that there was a clear distinction in the geochemical composition of the soils of the raised beaches and the moraine sediments.

3.3. Vertical and lateral distribution of the radionuclides

The artificial ^{137}Cs fallout was only found in the soils of the raised beaches with a mass activity range between b.d.l. and 10.1 Bq kg^{-1}. The contents of the environmental radionuclides (ERNs) were low with mass activities ranges (Bq kg^{-1}) between 4.4 – 27.1 for ^{226}Ra, 5.6 – 9.4 for ^{232}Th, 12.0 – 28.1 for ^{238}U and 190 – 276 for ^{40}K. The mean contents of ERNs were significantly higher in the soils of the raised beaches in comparison with contents in the moraine (Table 6). The largest difference in mass activity was for ^{226}Ra that doubled the contents in the moraine. ^{232}Th also showed similar patterns although differences between contents in both landforms were lower than for ^{226}Ra. The less differences although significant were for the ^{238}U means (Table 6). The range of variation of the ERNs was larger in the soils on raised beaches than in the moraine except for ^{40}K.

The depth distribution of the radionuclides showed distinctive patterns between the artificial fallout ^{137}Cs and the environmental radionuclides (Fig. 8). Depleted levels of ^{137}Cs were found at the topsoil of EP2, EP3 and EP5 and activities were negligible at the lowest layers of EP1, EP2 and EP4. The ^{137}Cs activity was the most variable with depth in comparison with that of ERNs, especially with that of ^{40}K, although ^{232}Th and ^{238}U also had a quite homogeneous distribution with depth. In the depth intervals the activities of ^{226}Ra were also variable and values were half in the moraine profiles than in the raised beaches.

4. Discussion

4.1. Soil forming processes

In comparison with colder areas in Antarctica the relatively rapid forming soils in Elephant Point are controlled by the comparatively more humid conditions favoured by the flat surfaces of the raised beaches that enable water retention and infiltration. Besides the frequent freeze-thaw cycles during summer that allows the circulation of water in the soil profile promoting the mobility of soil nutrients as well as the microbial activity would enhance the soil forming processes (Otero et al., 2013).

The soils existing in Elephant Point appear only close to the coast on the raised beaches.

They are poorly developed Cryosols (Michel et al., 2012), with no horizon differentiation apart from some layering of round gravels that are more abundant at deeper levels. The most distinctive feature is a relatively rich organic topsoil, defining and incipient organic horizon. Soil development on the raised beaches of Elephant Point is favoured by the warmer conditions existing in this western part of Maritime Antarctica in comparison with eastern parts. In summer, temperatures at sea level are around 0ºC (Oliva and Ruiz-Fernández, 2016) with frequent freeze-thaw cycles and significant precipitations – that amount 100 mm, 20 % of the annual rainfall (Bañón, 1992; Rakusa-Suszczewski, 2002) – that enhance chemical weathering processes and soil development.

On the moraine, sediments remain undifferentiated with no evidence of any early pedogenesis. The very scarce mosses covering some spots at the foot of the moraine close to the oldest raised beach do not have yet any effect neither on the organic carbon content nor on the pH values found at EP6. The short time since deglaciation is a key factor that explains the absence of vegetation and soil formation in the moraine. It is necessary to mention the important role played by birds in the dissemination of vegetation to the new ice-free areas, together with the role played by water and wind (Ruiz-Fernández et al., 2017). The angular shape of the coarse fractions in the moraine suggests that mechanical processes related to frost shattering on these recently exposed sediments are much more important that in the raised beaches. In contrast, the role of the sea action is clearly detected in the round shape of gravels in the soils of the raised beaches. This is furthermore confirmed by the grain size distribution in these soils with increasing contents of the coarsest fraction with depth, as well as the general abundance of sands.

In Elephant Point the soils of the raised beaches covered by mosses and with faunal activity are acidic in comparison with the almost neutral pH values found in the sediments of the upper part of the moraine and close to the glacier front. This pattern of pH values increase towards the glacier front with the higher values closer to the glacier, with the exception of EP1 located on the youngest raised beach, suggests that the moraine material is not inherently acidic. The acidification of soils of the raised beaches where nesting sites and bird activities take place is related to the mineralization of nitric and sulfuric acids released from guano (Bölter et al., 1997) and to humic and fulvic acids released by mosses (Bölter, 2011) besides mammals colonies also contribute to nutrient inputs. Therefore, the earlier deglaciation of this area subsequently uplifted by glacio-isostatic rebound throughout the Holocene (Fretwell et al., 2010; Watcham et al., 2011; Oliva and Ruiz-Fernández, 2016) explains why long-term biological activity had more time to acidify these soils.

Acidic pH values were also found at the upper part of soils on raised beaches located below 12 m a.s.l. in the nearby Byers Peninsula (Navas et al., 2008), whereas at higher altitudes and on bedrock plateaus and till substrates pH values were alkaline. Wilhelm et al. (2016) also found neutral pH locations in the proximities of retreating glaciers in Cierva Point (64ºS, western Antarctica Peninsula), indicating a geographical delimitation of pH values in function of the distance to the glacier.

The low salinity values especially at sites closer to the coast suggest the dilution of marine aerosols by melting waters or rainfall that infiltrates through the soil during thawing favoured by the flat surfaces of the raised beaches and by the fact that precipitation exceeds evaporation (Lee et al., 2004). Similarly, in Byers and Hurd Peninsulas salts did not accumulate in soils close to the sea (Navas et al., 2008), contrary to what Claridge and Campbell (1977) found in other Maritime Antarctica environments.

Comparing with the sediments of the moraine where SOC was not detected, soils on the raised beaches contained organic carbon in all depth intervals. Therefore, the strongest differentiation in both landforms was the presence of SOC and its accumulation in the top 3 cm defining an incipient organic rich horizon in the soils of the raised beaches. The presence of SOC is the most relevant feature indicative of the soil forming process in Elephant Point which is directly related with the occurrence of vegetation cover (mainly mosses and Antarctic grasses) favoured by the relatively mild climate conditions and the existence of biological activity (Ruiz-Fernández et al., 2017). In the nearby Byers Peninsula, several authors have confirmed its higher biodiversity (e.g. Convey et al., 1996; Quesada et al., 2009) likely due to the wind transport of propagules from South America coasts (Quayle et al., 2002; Quesada et al., 2009; Otero et al., 2013).

Despite the relatively low SOC contents in the Cryosols of the raised beaches they almost double those found in the nearby Byers and Hurd Peninsulas (Navas et al., 2008). The abundance of mosses explains also the highest SOC values in EP3 and EP5 similarly to the highest ones found in Byers and Hurd and in agreement with data from Bockheim (1997) and Beyer et al. (1998) as in the region humification is maximized (Bockheim and Ugolini,1990). Wilhelm et al. (2016) also reported accumulation of SOC in all moss-dominated soils in Cierva Point in the Antarctic Peninsula.

The absence of SOC in the moraine sediments shows evidence that pedogenesis has not occurred yet in this area where unconsolidated sediments are being mobilized by intense periglacial slope processes (Oliva and Ruiz-Fernández, 2015). Furthermore, the decreasing SOC content with depth in the soils of the raised beaches demonstrates a certain degree of soil development that is related to the earliest glacier retreat at these sites that were deglaciated before the moraine. This is further confirmed by the higher contents of SOC at sites EP2, EP3, EP4 and EP5 that doubled and even tripled those in EP1, the youngest raised beach, which in turn has the lowest content of the stable carbon fraction in comparison with the percentages recorded in the sites of the older raised beaches. Furthermore, the increasing content of SOC with depth and the presence of the stable carbon fraction only in the lower layer of EP1 may suggest the existence of a buried soil at this point.

The geochemical composition in the study sites is related to the lithology existing in Elephant Point consisting of basalts, schists with granodiorites and shales. As parent materials there are two main sources: moraine sediments and the sandy matrix rich pebbles of the raised beaches. The intense physical weathering through the freeze-thawing cycles produces a strong reworking of the materials. In the raised beaches its further classification under the intense sea action lead to the selection of the grain size fractions likely affecting as well its mineralogical composition. This is one of the reasons for the statistically significant differences in the means of the major elements Fe, Al, Ca, Na, Ti and Mg and of the minor and trace elements (i.e. Mn, V, Sr, Cd, Mo) found in the moraine and raised beaches sections; remarkably, the kind of elements and their relative abundance followed the same order in both landforms. In addition, the presence of mosses and ornithogenic activity in the raised beaches favour chemical weathering processes that intensely affect the soils in this area. The larger lateral variations in the contents of most elements in the raised beaches by comparison with the more homogeneous distributions in the moraine is likely due to the most active mineral weathering in the former. This is likely promoted by the more intense circulation of water in the soil profiles of the raised beaches favoured by deeper frozen ground conditions (active layer or seasonal frost regime) and their flat surfaces (Oliva and Ruiz Fernández, 2016).

The contents of the stable elements in Elephant Point are similar to that found in other ice-free areas in Livingston Island, such as Byers and Hurd peninsulas (Navas et al., 2008), though in Elephant Point Fe contents are higher. The mineralogical analyses done in this previous study revealed the presence of sheet silicates (chlorite, smectite, illite), quartz, potassic feldspars and alkali feldspars, zeolites and calcite to what the elemental composition was related. In Byers, chemical weathering although of limited extent (Navas et al., 2008) has been also reported by Moura et al. (2012) and Otero et al. (2013). Its influence on soil development has been already described in other ice-free areas in Maritime Antarctica (Blume et al., 1997; Beyer et al., 2000) fostered by the higher levels of moisture (Hall et al., 2002). Also in the Antarctic Peninsula, Wilhelm et al. (2016) found evidences of leaching and accumulation of clays and nutrients in soil profiles of Cierva Point revealing the effect of chemical weathering. However, at the higher elevations of the moraine the effect of the cycles of freeze–thaw weathering can be further restricted not only by the lower thickness of the active layer, but also due to the lack of vegetation cover together with the absence of seabirds colonies. Therefore, the stable elements in the active layer of the moraine sites reflect more closely the composition of parent materials than in the soils developed on the raised beaches because of the key control of the parent material geochemistry on the transfer of elements as it has been also reported in other cold environments (Navas et al., 2014).

The presence of fauna on the raised beaches, as penguin nesting sites, other seabirds and elephant seals together with the occurrence of mosses and grasses determine not only the lowest pH values found in the study soils but also the highest nutrient contents such as SOC and P. Besides the nutrient inputs from elephant seal colonies the presence of penguins and subsequent mineralization of calcium phosphates in guano (Wilhelm et al., 2016) leads to the accumulation of P in the surface soils of the raised beaches that double the contents in moraine sites. The enrichment in P of ornithogenic origin has been found in other Antarctica coastal environments (Blume et al., 1997; Beyer et al., 2000, Moura et al., 2012; Souza et al., 2014). However, our P levels are not as high as those reported by Wilhelm et al. (2016) in Cierva Point where the authors also relate the enrichment in nitric acids to ornithogenic activity. In addition, the H^+ inputs in the acidic soils will favour the leaching of stable elements causing the largest spatial variations detected in the soils of the raised beaches. This agrees with previous findings reporting accelerated mineral weathering associated to the activity of plants and microorganisms (Beyer et al., 1997; Allen, 2005; Otero et al., 2013). Boxma (1981) also points out that organic acids released by mosses favour the transport of iron chelates downwards through the soil and facilitate the mobility and bioavailability of macro and micronutrients (e.g. Dawson et al., 1984; de Mora et al., 1994; Munroe et al., 2007).

4.2. Tracing the glacier retreat

The variability of the environmental radionuclides (ERNs) in the study surface profiles is primary related to the mineral composition of the substrate. In agreement with their lithogenic origin, ERNs are generally associated to fine grain particles or fixed within the lattice structure of sheet silicates (e.g. VandenBygaart and Protz, 1995). Apart from ^{40}K the slightly higher variability of the depth distribution of ERNs found in the soils of the raised beaches suggest some mobility of the ERNs in this area. The higher water circulation in the flat raised beaches favoured by the inexistence of permafrost in this area (Oliva and Ruiz-Fernández, 2016) and acid pH values can favour such slight mobilization, while the ice-rich permafrost moraine would restrict more the water infiltration. The lateral and depth distribution of ERNs is primarily caused by geomorphic and soil processes affecting the parent materials. Hence, grain size classification and pedogenesis occurring in the raised beaches appears to be the main reason for the statistically significant differences in the means of the environmental radionuclides activities compared to the moraine sites with the largest difference for ^{226}Ra that doubled the content found in the moraine. As high carbonate contents can restrict the mobility of ^{226}Ra (Navas et al., 2002 a, b), the lack of carbonates in Elephant Point can further favour the mobilization of ^{226}Ra accounting also for its vertical variability. Similar differences were found in soils developed on different landforms that were deglaciated at different ages in glacial valleys of Norway (Navas et al., 2014).

Despite the few number of studies on the depth distribution of radionuclides in Antarctica our results match with the obtained in a previous research in Byers Peninsula that found a general common origin for the ERNs and larger variability of ^{40}K due to higher lithological diversity in the Byers transect (Navas et al., 2005a). Despite large environmental differences soil processes have been found to affect the vertical distribution of ERNs also in Pyrenean soils (Navas et al., 2002b). Although to a much lesser extent, the differential mobility of radionuclides of the U and Th series might occur in the soils of the raised beaches of Elephant Point as it has been found in a broad range of pH values (Harmsen and de Haan, 1980). However, in the moraine sites lower contents and less variation of ERNs might be more straightforward linked to original minerals as reported by Nielsen and Murray (2008) who found that ERNs are bound in primary minerals of sandy sediments of Jutland.

The presence of the artificially emitted ^{137}Cs that was only found in the soils of the raised beaches confirm that at the time of the peak fallout of ^{137}Cs, around 50 years ago since the date of sampling, only the soils of the raised beaches were able to fix the radionuclide in strong contrast with the moraine materials, subjected to reworking and mobilization slope processes. The raised beaches were deglaciated earlier and the fixation of ^{137}Cs was done by the fine soil components, clays and organic matter, which are very efficient fixing the radionuclide (Takenaka et al., 1998, Gaspar and Navas, 2013; Gaspar et al., 2013). As suggested by aerial photos, in 1956 the glacier was in contact with the internal area of the moraine system of Elephant Point (Oliva and Ruiz-Fernández, 2015). Therefore, the internal sector of the moraine and the present-day proglaciar area have been formed since that date. The absence of ^{137}Cs in the moraine is probably due to the fact that these materials were exposed after the deglaciation of this enclave. Other factors such as the presence of permafrost with a reduced active layer thickness and the steep slopes that would restrict the water infiltration making difficult the radionuclide fixation as well as the likely shorter periods of exposed surface in summer should not be discarded. Considering the age of ice retreat the oldest ice-free site is EP5 and the more recent is EP10, just few decades. Consequently, due to their recent exposure, soils have not developed and the lack of organic matter in the moraine sediments also hinders fixing the radionuclide.

The vertical migration of ^{137}Cs in the raised beaches has been limited as, apart the natural ^{137}Cs decay, is suggested by the negligible activities at lowest layers of EP2 and EP4. Below the surface the exponential decay of ^{137}Cs until undetected levels in lower layers of EP2, EP3 and from the topsoil at EP4 suggests that the soil on the raised beaches 2 to 4 has been almost stable since the peak fallout of ^{137}Cs. Depleted levels of ^{137}Cs at the surface of EP2, EP3 and EP5 might indicate some loss of fine particles in the topsoil, as its mobility is associated with that of soil (Navas et al., 2005a,b). This loss can be likely due to fauna activity as the raised beaches are flat surfaces and little soil movement by water erosion is expected to occur, although wind erosion should be also considered in such a windy area as the SSI (Bañón et al., 2013). The vertical ^{137}Cs profile at EP5 where high activities are found at lower layers suggest higher disturbance and soil mixing likely due to elephant seal and ornithogenic activity. At EP1 the absence of the radionuclide at lower layers in coincidence with the high contents of SOC support the existence of a buried soil of an age previous to the peak fallout of ^{137}Cs. Furthermore, the largely depleted levels at the upper part of the profile suggest high disturbance likely due to fauna, wind or sea action. The higher depth of penetration of ^{137}Cs in soils of Elephant Point (minimum of 12 cm at EP5 and EP3) than in Byers Peninsula where the radioisotope was undetected below 6 cm depth, despite being present at higher altitudes (Navas et al., 2005a), could probably be linked to the thicker active layer and the higher water circulation in Elephant Point. The ^{137}Cs activities were in general lower than in other polar environments such as inland Terra Nova bay (Sbrignadello et al., 1994). These lower activities can be due to differences in total rainfall but also related to more active processes in ice-free areas that could result in radionuclide losses.

These results show that the different processes operating in both landforms (raised beaches vs moraine) have generated distinctive properties that also affect the vertical and lateral patterns of the stable elements and radionuclides in the study profiles. Furthermore, the different patterns of ground thermal regime in both landforms (seasonal frost vs permafrost) further control pedogenesis by limiting the effectiveness of leaching processes when the thickness of the active layer or seasonal frozen ground is smaller, as it occurs in the moraine.

5. Conclusions

The lithologies of the surface formations in recently deglaciated areas together with geomorphic processes and fauna activity are key factors for soil development in this Maritime Antarctic region. In Elephant Point soil development only occurs in the raised beaches in the form of shallow and very poorly developed Cryosols that do not present horizon differentiation. These soils have been forming since their exposure by glacio-isostatic processes following the deglaciation of this area. Therefore, the oldest period of soil formation would correspond to the highest raised beach (raised beach 1, EP5) and the youngest to the lowest raised beach (raised beach 5, EP1), which is supported by the fact that the soil at EP1 located just 2 m a.s.l. has an almost neutral pH and pedogenesis is still limited.

Besides mineralogical composition, the duration of soil forming processes in the study sites also affects the abundance of the stable elements and environmental radionuclides. The geochemical variability found in the study profiles is linked with the mineralogical composition of the parent materials and the edaphic processes occurring in the raised beaches stimulated by the biological activity. The presence of ^{137}Cs in the soils of the raised beaches and its absence in the moraine sediments is related to glacial retreat and the nature of frozen ground conditions and associated geomorphic processes in both landforms.

The moraine was deglaciated more recently and soils had not enough time to develop from the unconsolidated sediments in such short period of time under Antarctic climate conditions. Besides, the presence of permafrost at 30-45 cm depth restricts water circulation during the snow melting season. However, the mosses specimens found at EP6 indicate an emerging early stage of soil formation in the oldest site of the moraine area.

If perspectives of warmer climate following the temperature rising trend observed since the 1950′s continue, then the number of freeze-thaw cycles during the summer season when these cycles are more frequent might increase, which may intensify soil development in the region. Furthermore, the incipient colonization by plants as observed in the moraine site EP6 will progress favouring the onset of the soil forming processes in the moraine, leading to increase acidification that would contribute to chemical weathering and accelerated pedogenesis. Consequently, changes in the active layer dynamics and permafrost distribution may occur affecting geomorphic activity as well as soil development. Moss growth may be faster than at present thus accelerating the soil forming process with important effects on the Antarctic terrestrial ecosystems.

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Figure captions

Figure 1.- Location of Elephant Point Peninsula in Livingston Island within the South Shetland Islands

Figure 2.- A) Main geomorphological units and landforms. B) Location of the samples along the study transect (dotted line) following the direction of glacier retreat. C) characteristics of underlying materials in Elephant Point Peninsula.

Figure 3.- Percentages of the coarse (> 2mm) and fine (< 2mm) fractions and contents of sand, silt and clay in the depth intervals of the sampling points and photos of the sections sampled along the transect.

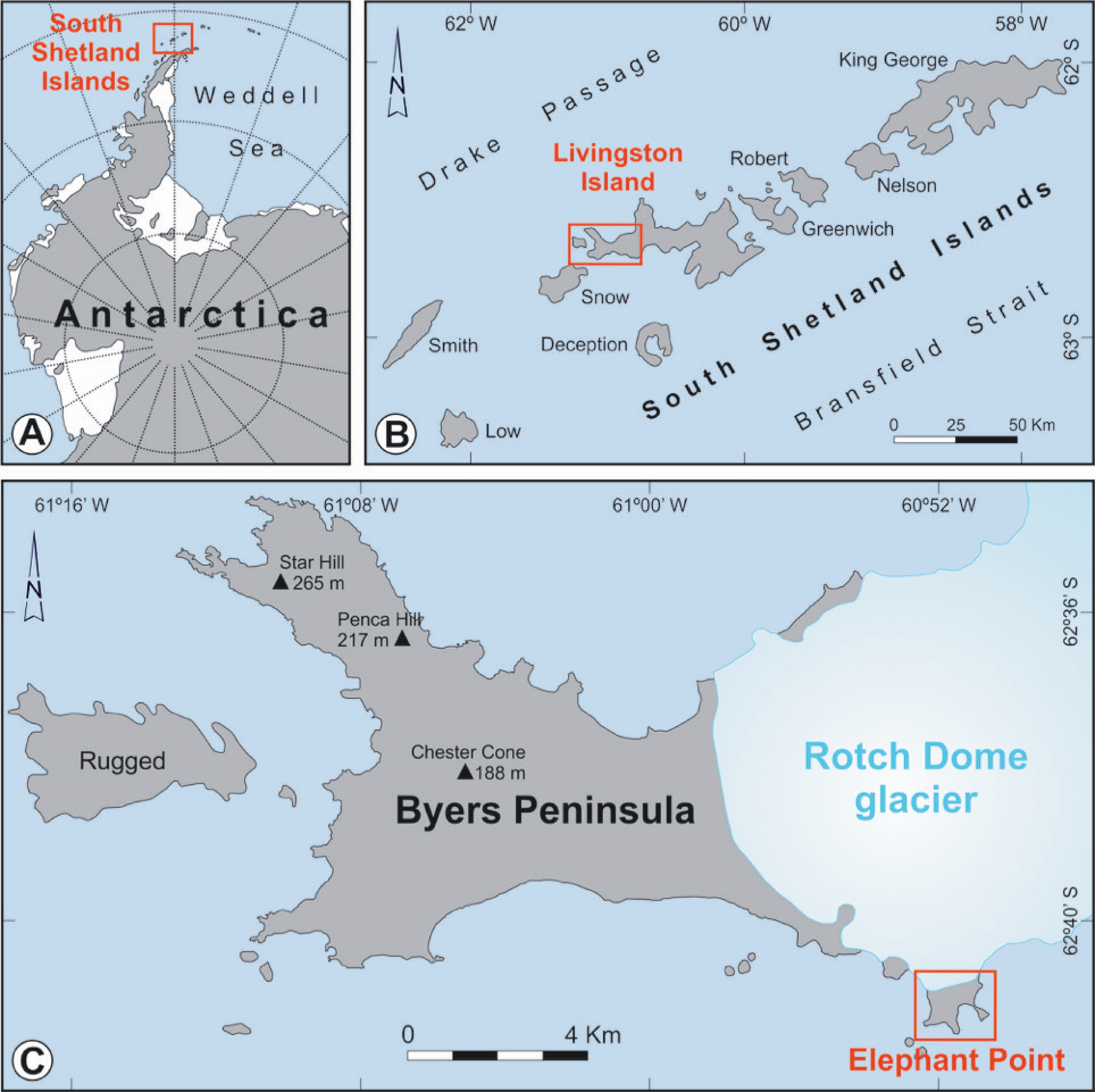
Figure 4.- Vertical distribution of the contents of soil organic carbon (SOC) and carbon fractions (ACF and SCF) in the study profiles of raised beaches and moraine along the transect.

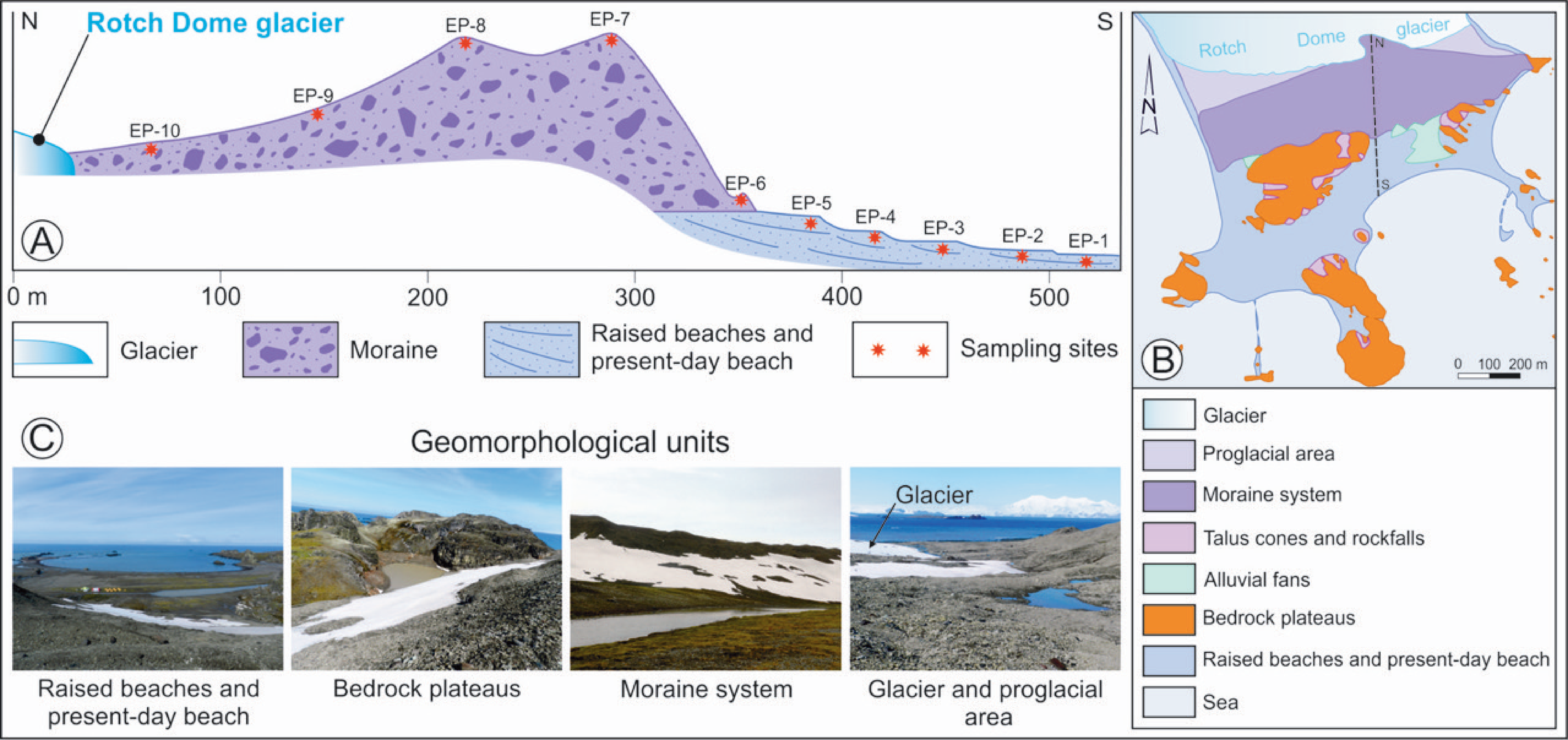
Figure 5.- Lateral variations of the mean values of the elements (mg kg^{-1}) in the study profiles along the transect starting from the Rotch Dome glacier (distance in m).

Figure 6. Vertical variations of some of the major stable elements in the sampling sites along the transect.

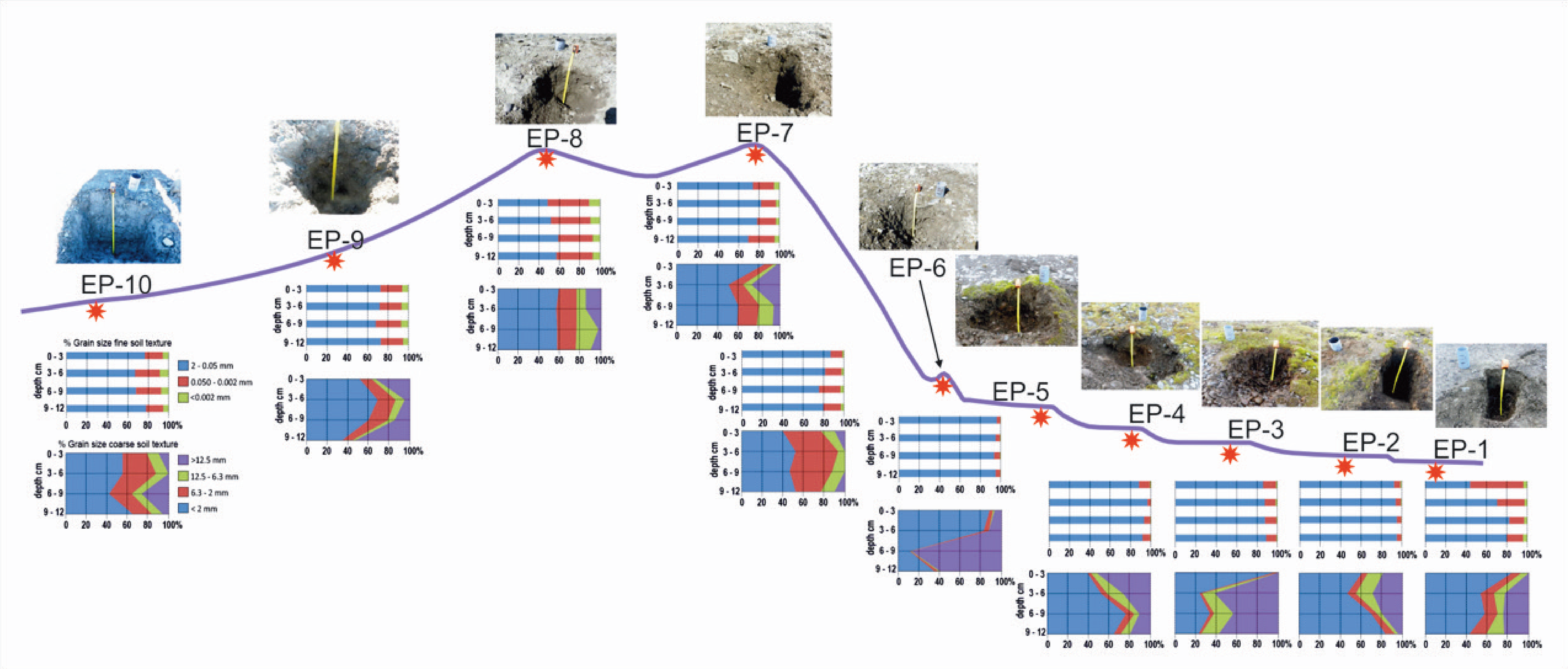
Figure 7. Plot of the Discriminant Function analysis including all the stable elements: Li, K, Na, Be, Mg, Ca, Sr, Cr, Cu, Mn, Fe, Al, Zn, Ni, Cd, Tl, Bi, V, Ti, Pb, B, Sb, P, S, Mo and Se, that differentiate raised beaches and moraine.

Figure 8.- Vertical distribution of the mass activities (Bq kg^{-1}) of fallout ^{137}Cs and environmental radionuclides (^{226}Ra, ^{232}Th, ^{238}U, ^{40}K) in the study profiles of raised beaches and moraine.


South Shetland Islands
Weddell
Sea
Antarctica
A
62º W
60º W
58º W
62º S
63º S
Drake Passage
Livingston Island
King George
Robert
Nelson
Greenwich
Snow
Smith
Deception
Low
South Shetland Islands
Bransfield Strait
0
25
50 Km
B
61º16' W
61º08' W
61º00' W
60º52' W
62º36' S
62º40' S
Star Hill
265 m
Penca Hill
217 m
Chester Cone
188 m
Rugged
Byers Peninsula
Rotch Dome glacier
0
4 Km
Elephant Point
C



N
Rotch Dome glacier
S
EP-10
EP-9
EP-8
EP-7
EP-6
EP-5
EP-4
EP-3
EP-2
EP-1
A
0 m
100
200
300
400
500
Glacier
Moraine
Raised beaches and present-day beach
Sampling sites
Rotch
Dome
glacier
N
S
B
0 100 200 m
Glacier
Proglacial area
Moraine system
Talus cones and rockfalls
Alluvial fans
Bedrock plateaus
Raised beaches and present-day beach
Sea
C
Geomorphological units
Glacier
Raised beaches and present-day beach
Bedrock plateaus
Moraine system
Glacier and proglacial area



EP-10
EP-9
EP-8
EP-7
EP-6
EP-5
EP-4
EP-3
EP-2
EP-1
% Grain size fine soil texture
% Grain size coarse soil texture
depth cm
0 - 3
3 - 6
6 - 9
9 - 12
0 20 40 60 80 100%
2 - 0.05 mm
0.050 - 0.002 mm
<0.002 mm
>12.5 mm
12.5 - 6.3 mm
6.3 - 2 mm
< 2 mm

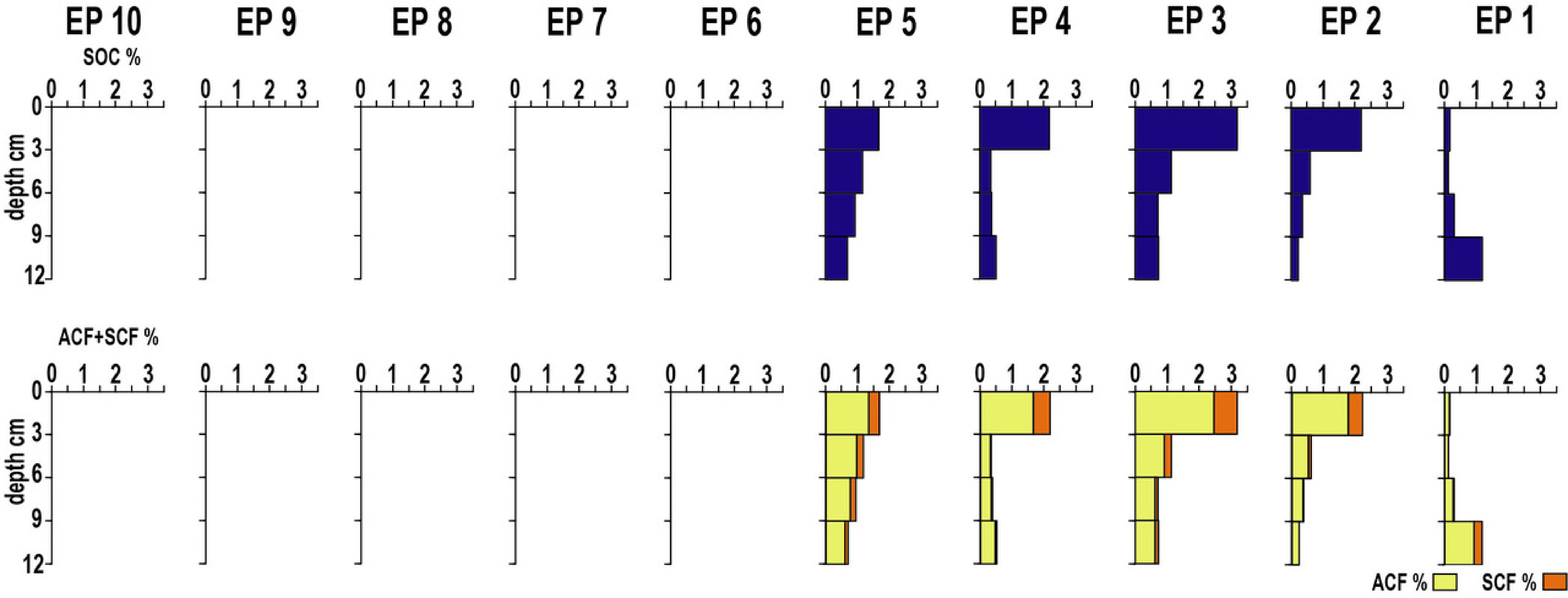

EP 10
EP 9
EP 8
EP 7
EP 6
EP 5
EP 4
EP 3
EP 2
EP 1
SOC %
depth cm
0 1 2 3
0 3 6 9 12
ACF+SCF %
ACF %
SCF %

Table 1. Location and characteristics of the sampling points along the study transect

	latitude	longitude	elevation m a.s.l.	landform	substrate	vegetation cover type	%	ornithogenic activity	material, shape	observations	thawed layer depth cm
EP1	62°41'12.1"S	60°51'33.0"W	2	raised beach 5	basalts	very scarce	2	abundant	round gravels	abundant matrix	unknown
EP2	62°41'11.0"S	60°51'35.0"W	3	raised beach 4	basalts	mosses and *Deschampsia antarctica* in cushions	25	abundant	round gravels	abundant matrix	unknown
EP3	62°41'10.4"S	62°41'10.4"S	5	raised beach 3	basalts	cushions of *Deschampsia antarctica* with mosses	50	abundant	round gravels	scarce matrix	unknown
EP4	62°41'10.0"S	60°51'37.6"W	7	raised beach 2	basalts	carpets and cushions of *Deschampsia antarctica* with mosses	70	abundant	round gravels	abundant matrix	unknown
EP5	62°41'9.9"S	60°51'38.8"W	10	raised beach 1	unknown, likely basalts	cushions of *Deschampsia antarctica* with mosses	20	abundant	round gravels	scarce matrix	90
EP6	62°41'5.9"S	60°51'34.3"W	49	glacial moraine (external moraine ridge)	“”	incipient mosses and isolated specimens of *Deschampsia antarctica*	5	scarce	angular gravels and pebbles	abundant matrix	65
EP7	62°41'2.7"S	60°51'34.1"W	51	internal moraine	“”	none	0	none	angular gravels and pebbles	abundant matrix	85
EP8	62°41'1.0"S	60°51'38.4"W	35	internal moraine	“”	none	0	none	angular gravels and pebbles	abundant matrix	45
EP9	62°40'55.8"S	60°51'35.6"W	27	moraine, glacier difluence	schists	none	0	none	angular gravels and pebbles	abundant matrix	50
EP10	62°40'52.9"S	60°51'36.8"W	24	moraine deposit in contact with glacier	schists	none	0	none	angular gravels and pebbles	abundant matrix	30

Table 2. Mean values of the main soil properties for each sampling point. -: non detected

	EP1	EP2	EP3	EP4	EP5	EP6	EP7	EP8	EP9	EP10
pH	6.37	4.52	4.60	4.87	4.54	5.97	6.70	6.10	6.73	6.67
EC dS m^{-1}	0.072	0.081	0.243	0.114	0.237	0.049	0.051	0.388	0.065	0.077
SOC %	0.452	0.846	1.439	0.854	1.120	-	-	-	-	-
ACF %	0.375	0.708	1.163	0.692	0.917	-	-	-	-	-
SCF %	0.077	0.138	0.277	0.162	0.203	-	-	-	-	-
Fine fractions %										
2000-50 µ	69.25	94.30	87.70	92.43	94.95	80.98	75.98	54.25	71.25	72.63
50-2 µ	27.43	4.98	11.13	6.80	4.55	16.50	19.85	37.13	22.50	20.85
< 2 µ	3.33	0.73	1.18	0.78	0.50	2.53	4.18	8.63	6.25	6.53
Coarse fractions %										
< 2mm	59.28	65.34	44.11	58.28	54.63	86.82	63.06	57.63	53.82	54.53
2-6.3 mm	12.81	7.45	3.34	5.99	3.25	9.02	15.73	18.47	14.53	24.11
6.3-12.5 mm	10.10	9.52	11.97	8.92	0.92	2.91	10.42	13.73	5.63	11.27
> 12.5 mm	17.81	17.68	40.58	26.81	41.20	1.25	10.79	10.17	26.01	10.09

Table 3. Basic statistics for the main properties assayed in raised beaches and moraine sampling points. SOC was not detected in the moraine.

	Raised beaches				Moraine				
	n	mean	SD	CV %	n	mean	SD	CV %	P-value
pH	5	4.98	0.73	14.6	5	6.43	0.34	5.3	**0.0000**
EC dS m^{-1}	5	0.149	0.08	51.7	5	0.126	0.14	106.9	0.5049
SOC %	20	0.942	0.811	86.1	20	-	-	-	
ACF %	20	0.771	0.616	79.9	20	-	-	-	
SCF %	20	0.171	0.197	115.1	20	-	-	-	
Coarse fractions %									
2000-50 µ	20	87.73	12.18	13.9	20	71.02	10.18	14.3	**0.0001**
50-2 µ	20	10.98	11.29	102.9	20	23.37	8.04	34.5	**0.0003**
< 2 µ	20	1.30	1.12	86.3	20	5.62	2.41	42.9	**0.0000**
Fine fractions %									
< 2mm	20	56.33	24.30	43.1	20	63.17	15.59	24.7	0.2957
2-6.3 mm	20	6.57	4.07	62.0	20	16.37	6.32	38.6	**0.0000**
6.3-12.5 mm	20	8.29	6.51	78.5	20	8.79	5.26	59.8	0.7879
> 12.5 mm	20	28.82	23.71	82.3	20	11.66	13.38	114.8	**0.0076**

Bold numbers are significant at the 95% confidence level.
SD: standard deviation, CV: coefficient of variation.

Table 4. Basic statistics for the geochemistry (mg kg^{-1}) assayed in marine terrace and moraine sampling points.

	Raised beaches (n=20)			Moraine (n=20)			
Mg kg^{-1}	mean	SD	CV %	mean	SD	CV %	P-value
Fe	57496.5	5412.7	9.4	53088.5	3459.0	6.5	**0.0040**
Al	45587.5	3704.3	8.1	49200.5	4545.8	9.2	**0.0089**
Ca	28431.5	2643.7	9.3	33687.0	1818.7	5.4	**0.0000**
Na	19296.0	1362.4	7.1	17888.0	1656.0	9.3	**0.0056**
Ti	7594.0	1089.6	14.3	5575.5	457.5	8.2	**0.0000**
Mg	6563.3	1429.8	21.8	8578.7	1253.1	14.6	**0.0000**
K	4968.9	489.1	9.8	5038.4	956.7	19.0	0.7740
B	1814.8	512.8	28.3	2860.5	383.6	13.4	**0.0000**
P	1591.8	342.9	21.5	727.3	106.4	14.6	**0.0000**
Mn	922.4	70.6	7.7	1008.5	68.8	6.8	**0.0004**
S	394.3	61.0	15.5	492.2	124.5	25.3	**0.0031**
V	209.9	20.8	9.9	195.5	11.4	5.8	**0.0098**
Sr	191.2	14.8	7.8	211.6	28.2	13.3	**0.0068**
Tl	79.7	7.4	9.3	82.4	5.3	6.4	0.1827
Zn	56.1	4.9	8.7	57.2	4.0	6.9	0.4574
Bi	49.6	4.2	8.5	43.3	2.2	5.1	**0.0000**
Cr	47.4	9.8	20.7	48.5	8.2	17.0	0.7212
Cu	22.4	7.4	33.2	49.8	5.1	10.2	**0.0000**
Pb	20.9	3.5	16.6	22.1	1.6	7.0	0.1444
Ni	17.8	3.1	17.4	18.4	3.8	20.8	0.5639
Li	6.9	1.7	25.2	11.5	1.5	13.2	**0.0000**
Rb	2.1	0.4	21.3	2.2	0.5	20.8	0.2261
Cd	1.2	0.4	32.7	0.5	0.2	52.6	**0.0000**
Mo	0.5	0.4	67.4	0.8	0.1	19.1	**0.0048**
Be	0.1	0.3	207.4	0.5	0.2	44.0	**0.0000**
Se	1.0	1.5	147.2	2.7	0.9	35.1	**0.0001**

Bold numbers are significant at the 95% confidence level.
SD: standard deviation, CV: coefficient of variation.

Table 5. Discriminant function coefficients used to discriminate amongst soils of raised beaches and moraine sediments.

	Funtion 1	Funtion 2
Al	0.547	-1.126
Be	3.296	2.877
Bi	-1.766	1.676
B	3.128	0.082
Ca	-1.866	0.817
Cd	-1.094	-0.615
Cr	2.777	-0.478
Cu	-4.113	-4.638
Fe	0.217	-0.880
K	1.751	-1.554
Li	-3.995	0.704
Mg	0.522	-2.731
Mn	-1.175	0.978
Mo	-0.157	0.138
Na	0.387	-4.323
Ni	-1.409	-0.178
Pb	0.104	-0.290
P	0.840	-2.260
Rb	-4.065	2.070
Se	-1.746	-0.275
S	1.627	1.945
Sr	0.933	2.772
Ti	-0.353	-0.072
Tl	1.764	2.128
V	0.603	2.362
Zn	0.510	-0.552

Table 6. Basic statistics for the mass activity of the natural and artificial radionuclides (Bq kg^{-1}) assayed in the study surface profiles on raised beaches and moraine sites. ^{137}Cs was not detected in the moraine.

	Raised beaches (n=20)			Moraine (n=20)			P-value
	mean	SD	CV %	mean	SD	CV %	
^{137}Cs	2.53	2.53	99.8	-	-	-	
^{226}Ra	15.34	5.80	37.84	7.70	2.48	32.21	**0.0000**
^{40}K	248.85	16.36	6.6	224.65	28.95	12.9	**0.0024**
^{232}Th	7.46	0.96	12.8	6.56	0.72	10.9	**0.0017**
^{238}U	21.08	3.38	16.1	18.32	2.73	14.9	**0.0071**

Bold numbers are significant at the 95% confidence level.
SD: standard deviation, CV: coefficient of variation.