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Soil characteristics on varying lithological substrates in the South Shetland Islands, maritime Antarctica

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Abstract

Soils in ice-free areas of Livingston Island have been forming since the last deglaciation in a maritime warmer climate that is more humid than in interior Antarctica. A soil survey was carried out on Byers and Hurd peninsulas to characterize the soils and investigate the processes. Soils were sampled on two different substrates, mudstones and volcanic rocks in Byers Peninsula and greywackes in Hurd Peninsula. Sampling sites were located on raised beaches, platforms, and on volcanic outcrops across an altitudinal range from few m to 150 m a.s.l.. The pH, electrical conductivity, carbonates and organic matter showed similar patterns in each geomorphic unit but their values differed between bedrocks. The sand, silt and clay contents differed greatly in the soils on mudstones and volcanic rocks. The elemental composition was closely related to mineralogy of parent materials. Mg, K, Zn, Mn, and Fe were similar in the soils on all bedrocks. The Al content was highest on the volcanic rocks. The largest difference in the Ca content was between the soils on greywackes and mudstones. The Na, Pb, and Ba contents in soils on the mudstones differed greatly from the rest of bedrocks. Geochemical and mineralogical characteristics suggest that the main process involved in soil development was the mechanical disintegration of bedrock although there was also some leaching. Cryogenic processes play a key role in soil development but chemical weathering processes were also involved in soil evolution although limited in extent due to the restriction of water circulation to summer.

Key words: Soils, Properties, Geochemistry, Permafrost, Byers Peninsula, Hurd Peninsula, South Shetland Islands, Antarctica

1. Introduction

The studies on soil characteristics are rare in Antarctica and the soil forming processes operating under extreme climate are not thoroughly understood. Soils can be a source of information on environmental changes as they provide a record of past and present conditions. In maritime Antarctica, including part of the Antarctic Peninsula and a series of islands, climate conditions are the warmest and moistest within Antarctica. Soils in this region are suggested to have formed since the last deglaciation which started ca. 9500–6000 yr BP. Because in this area there is a pronounced thaw period during the summer, soil development is more rapid than in other Antarctic regions where soils thaw to depths of less than 50 cm.

Due to the scarcity of ice and snow-free areas (in general, less than 1 % of the Antarctic land area), little is known on the influence of permafrost on soil formation. The presence of underground ice affects the distribution of components in water and in the solid phase of soils (Lee et al., 2004). The general conclusion is that soil formation is largely influenced by physical processes (Jie et al, 2000). The presence of patterned ground indicates the predominance of cryoturbation (Campbell and Claridge, 1987). A first survey of soils of the South Shetland Islands and adjacent parts of the Antarctic Peninsula, including observations on Byers Peninsula and other places of Livingston Island, was carried out by Everett (1976). Other studies on soils, landscapes and shelf sediments of coastal areas have been carried out in maritime Antarctica more recently (Blume et al., 2001; Jeong et al., 2004).

Studies on the distribution of permafrost (e.g. Bockheim, 1995) and on the characteristics and fragility of Antarctic Gelisols (e.g. Beyer et al. 1999) outline the existence of differences according to latitude and proximity to the coast. Relatively high soil water contents and accumulation of organic matter occur in some areas of the Antarctic Peninsula region in comparison with interior Antarctica. Previous research in the South Shetland Islands (Serrano et al., 1996; Serrano and López-Martínez 2000) identified the presence of ice-cemented permafrost with an active layer of about 30 cm, but the thickness of permafrost remains unknown. Climatic conditions in maritime Antarctica allow the presence of melting and liquid water in summer in the active layer and interacting with the upper part of permafrost, in contrast with the ice-free permafrost existing in colder and dryer Antarctic regions (Bockheim, 1995).

This study is part of long-term research on the soil formation and geomorphic processes in maritime Antarctica. A preliminary study on Livingston island was previously carried out by our group (Navas et al., 2006) along one transect in which four surface soil samples were analysed. In the present work a more representative sampling of the soils on Livingston Island, including deeper soil profiles and more sampling sites was made. The aim was to focus on the characterization of soils: general properties, geochemistry and mineralogical composition to assess the main soil forming processes and evolution under different lithological substrates. Representative soil profiles from Byers and Hurd peninsulas were collected from varying geomophological surfaces and altitudes. This work contributes to improved knowledge of soils and the processes involved in their formation under the presence of permafrost in maritime Antarctica.

2. Materials and methods

2.1 Study area

The South Shetland Islands constitute an island arc formed by eruption of magmas over a deformed sedimentary basement (Smellie et al., 1984) that was active from the Jurassic until the Quaternary (Smellie, 2002). Byers and Hurd peninsulas are located on Livingston Island (Fig. 1) (aprox. 62º 37' S - 61º 6' W) under the characteristic weather conditions of maritime Antarctica. Byers Peninsula is the largest ice-free area in the archipelago (around 60 km^2). The rock outcrops in Byers Peninsula are mainly mudstones, sandstones, conglomerates and volcanic and volcaniclastic rocks (Upper Jurassic to Lower Cretaceous) intruded by igneous bodies (e.g. Smellie et al. 1984; Crame et al. 1993). On Hurd Peninsula the bedrock is composed of greywackes, arenites and shales of the Miers Bluff Formation of possible Triassic age (Smellie et al., 1984).

Byers Peninsula is characterized by the presence of extensive raised marine platforms and beaches, jointly with erosive and depositional features of glacial origin and a well developed drainage system, with many streams active in summer and more than 60 lakes (Fig. 2). All these features, including the landforms and surface deposits of different origins have been represented in a geomorphological map of the Peninsula at 1:25000 scale (López-Martínez et al., 1995) and information on geomorphology and Quaternary evolution has been compiled (López-Martínez et al., 1996). Hurd Peninsula is ice covered in the central and northwestern sectors, and rock outcrops concentrate mainly along the coast and in the southeastern end (Fig. 3). Glacial lobes and tongues have formed small valleys and coves separated by relatively steep terrain. Raised beaches and marine platforms occur although they are less developed than in Byers Peninsula.

Periglacial landforms and processes are common in the ice-free studied areas. The presence of permafrost at depths at between 25 and 75 cm was identified at several places, being altitude an important factor for its distribution. The distribution of some periglacial features as patterned ground, stone stripes and gelifluction, pointed out the presence of permafrost in the studied region (López-Martínez et al., 1995). The patterned ground is present at altitudes above 30 m a.s.l. in areas relatively flat and with rock fragments of appropriate size. Continuous permafrost occurs above 30 m a.s.l., below this altitude permafrost is discontinuous and close to sea level only exists under special circumstances. The geomorphological and hydrogeological processes in the area reflect the presence of permafrost and an active layer (López-Martínez et al., 1996, Cuchi et al., 2004).

The last major deglaciation of the peninsulas began around 5-4 Ka BP (Björck et al., 1991, 1996; Björck and Zale 1996). The climate during the summer is characterized by frequent precipitation, presence of clouds, mean daily temperatures above 0ºC, and with moderate thermal amplitude. According to data recorded in Fildes Peninsula and Admiralty Bay, King George Island and on Hurd Peninsula, the mean annual temperature on Livingston Island is about –2º C at sea level and annual precipitation reaches 800 mm (Blumel and Eitel 1989; Rakusa-Suszczewski 1993; Bañón 2001). These climatic conditions are responsible for the soil differences that have been found between maritime Antarctica in relation to other Antarctic areas (Allen and Heal 1970; Everett 1976; Campbell and Claridge 1987).

Soils of the study areas are classified as Cryosols (ISSS – ISRIC-FAO 1998). Where permafrost is within 100 cm of the soil surface the soils are classified within the Gelisol order of the US Soil Taxonomy (Soil Survey Staff, 2006). Cryosols contain a cryic horizon or gelic materials in the case of Gelisols, resulting from cryogenic processes in the presence of permafrost.

In Byers and Hurd peninsulas, the high stoniness was one of the main characteristic of soils that were very poorly developed, with almost no horizon differentiation. Snow covered the soil surface for most of the year and vegetation was scarce. However, the ice-free areas of Livingston Island have a relatively high biodiversity (Sancho et al., 1999, Soechting et al., 2004). In the soils on the high platforms and other reliefs there are lichens on rock outcrops and stony soils. Lichens are usually located on areas with positive relief where wind favours snow-free surfaces, whereas mosses develop on finer grained soils and in small depressions. On the beaches the vegetation was also scarce and was mainly grasses (*Deschampia*).

2.2. Soil sampling

During the Antarctic summer periods of 2001, 2002 and 2003 a soil survey was carried out in the ice free areas of Livingston island to select representative locations on varying bedrock types, altitudes, and geomorphological units (Table 1) (López-Martínez et al., 1995). A total of 11 soil profiles of 10 to 50 cm deep were described and sampled. The sampling depth was selected to include the soil section where processes are supposed to be most active. The presence of permafrost and large stones and rocks restricted the sampling depth to a maximum of 50 cm. The sampling sites were excavated in order to extract samples in cylindrical containers, thus maintaining their original volume and position. Subsamples were obtained after sectioning the soil samples at regular depth increments (5 to 10-20 cm), due to the lack of clear soil horizon differentiation. In three profiles which displayed colour and grain size differences, these were used for sectioning the samples.

In Byers Peninsula, seven soil profiles were sampled (Fig. 2). Profiles B1 and B2 correspond to Holocene beaches (d-c transect). On the raised marine platforms, three profiles were collected. Profiles B3, B4, B5 (a-b transect) were located at hillslope, midslope and bottom slope positions at altitudes of 88, 70 and 72 m a.s.l, respectively. On volcanic plugs two profiles (B6 and B7) were collected. Profile B6 was collected close to Usnea peak at 108 m a.s.l and profile B7 was located on Chester Cone peak (188 m a.s.l).

In Hurd Peninsula, four profiles were collected at two locations from two soil sites each (Fig. 3). Profiles H1 and H2 (e-f transect) are in the vicinity of the Spanish Antarctic Base Juan Carlos I. H1 is on a Holocene raised beach at 5 m a.s.l.. Profile H2 is close to Radio Peak at 125 m a.s.l,. Profiles H3 and H4 were taken in the area of Sally Rocks (g-h transect). Profile H3 is on a stony Holocene beach at 6 m a. s.l.. Profile H4 is located at 155 m a.s.l in the southern sector of the Peninsula.

2.3 Soil analyses

Soil samples were stored at 4º C until analysed in the laboratory. Samples were air-dried, ground, homogenized and quartered, to pass through a 2 mm sieve. General soil properties analysed were pH, electrical conductivity (EC), carbonate content, organic matter (OM), total organic carbon (TOC), total nitrogen, extractable phosphorous and potassium (CSIC, Consejo Superior de Investigaciones Científicas, 1976), granulometric analysis of coarse fractions (>2 mm) and texture of the fine-earth fraction (<2 mm). Analysis of the clay, silt and sand fractions were performed using laser equipment. To eliminate the organic matter, samples were chemically disaggregated with 10 % H_20_2 heated to 80º C, then stirred and ultrasound was also used to facilitate particle dispersion. pH (1:2.5 soil:water) was measured using a pH-meter. Organic matter was determined by the Sanerlandt method (Guitian and Carballas, 1976) using a titrimeter with selective electrode. Carbonates were measured using a pressure calcimeter (CSIC, 1976).

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 17 elements: Li, K, Na (alkaline), Mg, Ca, Sr, Ba (light metals) and Cr, Cu, Mn, Fe, Al, Zn, Ni, Co, Cd and Pb (heavy metals). Analyses were performed by atomic emission spectrometry using an inductively coupled plasma ICP-OES (solid state detector). Concentrations, obtained after three measurements per element, are expressed in mg/kg.

The mineralogical study was made by means of X-ray diffraction using a difractometer equiped with a Si-Li detector using Cu Kα radiation on random powder of bulk sample. The <2μ fraction was studied on oriented samples after standard treatments. The reflecting powers of Schultz (1964) for bulk sample were used for the semiquantitative estimation of the identified minerals.

An ANOVA test was used to analyse the fixed effect of the physiographic location, geomorphological units and bedrock types on soil properties and major and trace elements. The data were analyzed using the least square method of the GLM procedure (SAS statistical package) to assess differences among the means. The correlation matrix was calculated for the response variables studied.

3. Results

3.1 Soil properties

In Byers Peninsula, the materials in profiles B1 and B2 are sand and microconglomerates including volcanic fragments and clays. Rests of algae and pebbles (2 to 10 cm long) at the soil surface, some with oxide coatings, are found at B1 (7 m a.s.l.) which is the most modern beach, whereas at B2 (10 - 11 m a.s.l) that is located close to a volcanic stack the soil surface consist of gravels (2 -5 cm diameter). Profile B3 presents large and angular pebbles (15 cm) of lutite and chert and abundant calcite veins. B4 is on soil stripes and materials are micronconglomerates and sandy pebbles with lutites also with some calcite veins. B5 is also on soil stripes of similar materials but with less calcite veins and smaller pebbles (2 - 10 cm). Profile B6 is a stony soil with angular pebbles (2 - 10 cm) of sand, microconglomerates and abundant calcite veins, the presence of permafrost was detected at 25 - 30 cm depth. Profile B7 is a silty-sand soil with some angular pebbles.

In Hurd Peninsula, profile H1 has small rock fragments from the Miers Bluff formation and dikes and was mainly composed of black sands. Profile H2 is a stony soil with abundance of lichens and volcanic ashes. Profile H3 is stony with pebbles round and angular, the latter coming from disintegration of nearby stacks. The materials are greywackes, arenites and piroclastic and volcanic ashes. The upper horizon has some organic material that is covered with mosses and grasses. Profile H4 has a soil surface covered by stones of various sizes (2 -50 cm) although the most abundant are between 5 to 9 cm. Greywackes predominate with shales together with some piroclastic and volcanic ashes.

The results of the main soil properties in Byers and Hurd peninsulas are presented in Table 2 with statistical analyses included in Table 3. In Byers Peninsula the raised platform soils were alkaline (7.9 to 8.2). On the beaches, the soils were acidic with the lowest values (5.5) found close to the sea. Similar results are observed in Hurd Peninsula. The average carbonate content was low and varies from undetected to more than 6 %. In agreement with pH distribution, some of the lowest values are in soils of the beaches. The highest percentages are associated with the presence of calcite veins; contents of 5 % are in the deepest layer of B6 and reach 20 % in deeper layers of B3 profile. These data are also supported by the results of mineralogical analyses that identified calcite in these profiles (Table 4). The highest content of carbonate in deeper soil layers may suggest some leaching. In soils of Hurd Peninsula the carbonates are almost non existent, calcite veins were not encountered in field observations neither on the mineralogical analyses of the profiles. Similarly, in Fildes Peninsula of King George Island, Zhao (1995) did not find $CaCO_3$ in most soils despite the existence of carbonates in the material, suggesting that decalcification occurs rapidly in cold wet soils. However, the presence of permafrost may reduce leaching in some soils.

Soil salinity was very low in all soils ranging from 0.03 dSm^{-1} in the beach profile (H1) to 0.15 dSm^{-1} in the soil on the volcanic plug (B6). Although higher EC would be expected in soils of the beaches, the low values encountered suggest the little effect of marine aerosols on soil salinity. These could be diluted by continental waters either as overland flow after melting ice or by fluctuations of water along the soil profile within the active layer during the thawing period. In the beaches of Byers and Hurd peninsulas, soluble salts were not accumulated in the soils in opposition to what Claridge and Campbell (1977) found in other locations in Antarctica. However, in agreement with Lee et al. (2004) in our study area precipitation exceeds evaporation and leaching of salt particles occurs through all soil profiles on the beaches even in those very close to the sea where marine aerosols are more abundant.

Organic matter and total organic carbon (TOC) contents are low in most soils. The highest percentages occur in B7 and H3 as these soils are covered by mosses and lichens, especially mosses are abundant at the volcanic Chester Cone in Byers Peninsula whereas at the beach site in Hurd Peninsula there are grasses but also inputs from seabirds. The low contents in OM and TOC are in agreement with data from Bockheim (1997). Bockheim and Ugolini (1990) indicate that humification is maximized in the region. Its origin appears to be mainly related to the presence of vegetation cover, especially mosses. Beyer et al. (1998) also suggest this origin for the recent organic matter. However, the less abundant vegetation cover at Hurd Peninsula in comparison with Byers Peninsula seems to be the reason for their lower OM and TOC contents, except in the beach profile H3 where inputs from seabirds are responsible of the relatively high OM, TOC and N contents. To this respect, Blume et al. (1997) and Beyer et al. (2000) indicated the strong effect of seabirds on nutrient contents in coastal locations of Antarctica.

The total nitrogen content is very low in most profiles and the average contents vary between 0.01 and 0.24 %. Similarly to organic matter and TOC, the highest values are found in profiles H3 and B7. The extractable phosphorous shows a wide range of variation from almost non existent in B7 to very high values in B5. In deep layers of B5, the high contents (41 - 52 mg/100g) could be due to the existence of P-rich minerals (apatite). In addition, because high K (13500-14900 mg kg^{-1}) occurs in the same layers of B5, the P-rich minerals could be associated with K-feldspars that are abundant in this profile. In the beach profiles, extractable P contents are low apart from H3 which coincides with high organic matter contents probably from guano inputs. The extractable K shows a wide range of variation and the highest and lowest values are both found in Byers Peninsula in the beach profiles and on the raised platforms profiles, respectively.

It is widely recognized that in the Antarctic environment physical processes and rock disintegration largely influence soil formation, therefore analyses of grain size distribution may help to interpret the role of such processes on the soil development on different bedrocks (Campbell and Claridge, 1987). The distribution of the coarse grain size fractions is highly variable. In agreement with field observations, higher stoniness is associated to the presence of sedimentary rock outcrops close to the sampling sites which is the case of profiles B6 and B3 whereas disintegration of volcanic rocks lead to finer grain size as in B7. The predominance of coarse fragments (> 12.5 mm) at the soil surface in all soil profiles of Hurd Peninsula, could be related to higher intensity of cryogenic processes or to its distinctive effect on the different bedrocks of Hurd Peninsula by comparison with those of Byers Peninsula (Figure 4). The abundance of coarse material is related to cryogenic processes and in general they predominate at upper landscape positions. The patterned ground is found on flat surfaces and its presence is more common in Byers Peninsula but less in Hurd Peninsula where steep slopes predominate. At the platform transect in Byers and although coarse materials can be transported downslope, the normal pattern of soil redistribution as a result of the processes of grain size classification determines the abundance of fine materials at bottom slope positions (Navas et al., 2006).

The contents of the fine fractions (< 2 mm) are also highly variable. The differences found in soil textures are caused by the variety of parent materials on which soils are developed. In Byers Peninsula, the sand fraction predominates in the soils of the volcanic plugs that have loamy-sand textures. On the marine platforms, the abundance of silt is related to the mudstone outcrops and soils are silty loam. From the platform towards the raised beach, silt and clay contents decrease and sandy textures predominate in the soils of the Holocene beaches. In Hurd Peninsula all soil profiles have sandy-loam textures.

Concerning the variations of soil properties with depth, both coarse and fine fractions show very diverse patterns. As shown in Figure 4, for the coarse fractions there is an increase with depth of the < 2.0 mm fraction in the profiles B2, B4, and B7 and in H1 and H2 but the contrary is observed in B1, B3, and B6 and in H3 and H4 where the > 2 mm fractions increase with depth. The distribution of sand, silt and clay with depth shows comparable patterns for the soils within each different geomorphological unit at Byers Peninsula, whereas all soil profiles at Hurd Peninsula show very similar grain size distributions.

In the soil profiles (Table 2) and apart from B4, the pH slightly increases with depth. The variation of EC with depth does not show any special pattern but uniformity is more general in the soil profiles at Hurd Peninsula. The main features in the variation of carbonate contents are the increases observed at deeper layers in the profiles B3, B4 and B6 which are associated with the presence calcite veins. The organic matter and TOC contents have similar depth profile distributions. Although, in general, there are little variations slightly higher contents are observed at the soil surface, especially in most of the beach profiles. The depth distribution of N exhibit different patterns although in parallel with organic matter, the most common is the existence of slightly higher contents at the soil surface. The extractable phosphorous shows in general little variations with depth apart from the peaks at deeper layers in B5 and B6 that might be related to mineralogy, and to seabirds inputs in H3. The extractable potassium has very irregular depth distribution in all profiles and this is probably related with the total K concentration.

3.2. Soil mineralogy

The mineralogical composition of the soil profiles at Byers and Hurd peninsulas are summarised in Table 4 and Figure 5. In the soils of Byers Peninsula the most abundant minerals are feldspars (50%). The plagioclases are predominant and in some samples they are the only feldspars present. An exception is the volcanic profile (B7) at the Chester cone, where the potassic feldspars are equally or more abundant than the plagioclases. The mineralogy in B7 is clearly different from the other profiles as it is mainly composed of feldspars with occasional quartz, zeolites and sheet silicates.

In all the soil profiles and apart from the predominance of plagioclases, there are zeolites, e.g. laumontite (5 and 28%). In one rock fragment harmotome-phillipsite is present. Another main component is quartz (below 20%). Sheet silicates are also quite abundant (11 to 43 %) and are composed of chlorite and smectite that generally form irregular interstratified minerals with variable predominance either of chlorite or smectite. Very low quantities of hydrous mica are occasionally detected. The origin of chlorite in these soils appears to be mainly derived from glacial erosion and the physical weathering of the parent materials. The smectites may be derived from weathering of “in situ” volcanic rocks.

Calcite was only detected in B3 with up to 42 % in deeper layers. Less than 10 % Calcite was reported in B4 and also in the deepest layer of B3. High percentages (up to 45 %) of calcite were found in the deepest layer of B6, probably due to the weathering of calcite veins.

Zeolites were abundant in B2 and had low contents in B7. The origin of zeolites is the weathering in situ of volcanic bedrocks as they are present infilling cavities in rock fragments of the soils. However, it has not been found any special variation in the mineralogical composition along the soil profiles as to establish any general trends in the soil development and its evolution.

The mineralogical composition of the soils in both peninsulas is different (Table 4, Figure 5). Thus zeolites and calcite are not present in the soils of Hurd Peninsula, and quartz and sheet silicates are almost non existent or in very small amounts. The most abundant minerals from the Hurd Peninsula soils were feldspars of which two main types are encountered, with potassic feldspars predominating over the plagioclases which is the opposite to what it was found in the soils of Byers Peninsula.

In spite of the mineralogical uniformity found in the soils of Hurd Peninsula there is some exception in the deep layers of profile H4 where samples are richer in quartz and also sheet silicates are abundant. This sample was analyzed by XRD through preparation of an orientated sample of the < 2μ fraction and after the regular treatments it was found that illite was the predominant mineral, followed by chlorite, and that in both cases they had low crystallinity.

According to the mineralogical composition the soils of Hurd Peninsula appear to be compositionally more immature than soils of Byers, as its composition is dominated by non clay silicate minerals. The abundance of sheet silicates in the soils of Byers Peninsula may suggest a more intense weathering, although the interstratified minerals are identified in the parent materials and do not show important transformations in the soils. Therefore chemical weathering appears to be of minor relevance in comparison with physical weathering. Jeong and Yoon (2000, 2001) and Jeong et al. (2004) studied clay particles in sediments of South Shetland Islands and identified interstratified of illite-smectite and chlorite-smectite. These authors concluded that the erosion of the hydrothermally altered basic volcanics was likely to be the major source of smectite, chlorite and illite in the sediments

3.3. Elemental composition

Figure 6 presents the average contents and standard deviations of the studied elements in the soil profiles of the Byers and Hurd peninsulas. Fe and Al are the most abundant elements in all soils (Table 5). Iron contents with similar means in soils from Byers and Hurd peninsulas (48000 mg kg^{-1}), range between 39000 to 52000 mg Kg^{-1} and show less variation in Hurd Peninsula soils. The average Al contents are slightly lower in Hurd profiles and vary between 36000 to 52000 mg kg^{-1}. Similarly to Fe, the highest content is in B6. The average Ca content is slightly higher in the soils of Hurd Peninsula, its range varies between 11000 mg kg^{-1} (in B5) and 39000 mg kg^{-1} in

H3 where Ca might be associated with feldspars and sheet silicates. The high Ca content in B3 (38000 mg kg^{-1}) is associated to the presence of calcite veins, as the mineralogical and carbonate data indicate. The average Na content is also slightly higher in Hurd than in Byers profiles. Its range varies between 12000 mg Kg^{-1} (in B5) to 31000 mg Kg^{-1} (in B1). In general, the variations of the four main major elements Fe, Al, Ca and Na, follow similar patterns in all the profiles.

The mean Mg contents were similar in both peninsulas ranging between 5000 and 8000 mg kg^{-1} in B6 and B3, respectively. The average K contents are higher in Byers than in Hurd profiles and show large variations in the raised platform soils (3000 mg Kg^{-1} in B4 to 12000 mg kg^{-1} in B5). This difference may be explained by the mineralogy of the more abundant clay fraction in deeper layers of B5. The mean Mn contents are quite uniform in soils of Hurd and in soils on the volcanic plugs of Byers with values ranging between 840 and 950 mg kg^{-1}. The largest differences occur in soils on the raised platforms, thus contents in B3 at the hillslope position (1700 mg kg^{-1}) are four times those in B5 at the bottom slope position (400 mg kg^{-1}). This large difference must be related with the abundance of coarse fragments and with the mineral composition in B3. The minerals containing Mn could be related to the high carbonate contents in agreement with the presence of calcite veins. The beach profiles also present important differences in the average Mn contents, H1 which is closer to the sea, has lower Mn contents (700 mg kg^{-1}) than H2 (1100 mg kg^{-1}).

The average Ba content varies from 150 to 1300 mg kg^{-1}. The contents in the soils of Hurd Peninsula (900 to 1300 mg kg^{-1}) double those in soils of Byers Peninsula where the Ba content (150 - 200 mg kg^{-1}) in the raised platform profiles are five times lower than those in the beach profiles. The mineralogy explains the relatively high Ba contents in some of the profiles. The occurrence of Ba is usually linked with alkali feldspars (Kabata-Pendias & Pendias, 2001) and the highest feldspar contents are in Hurd profiles. The average content of Pb ranges between 200 and 1200 mg kg^{-1}. Conversely to Ba, the highest Pb contents are in the raised platform profiles of

Byers Peninsula. According to Norrish (1975), Pb is associated mainly with clay minerals which are relatively abundant in the raised platform profiles.

The average Sr content is slightly higher in Hurd than in Byers and contents vary from 100 to 300 mg kg^{-1} in B5 and H3, respectively. The parent materials may also have an influence on Sr distribution that could be related to the presence of feldspars. The average Zn content varies between 70 and 190 mg kg^{-1}. In general, Zn content is enhanced in argillaceous materials and shales (Kabata-Pendias & Pendias, 2001), which could explain the higher Zn contents in Hurd than in Byers profiles. The average Li content is generally uniform, and varies little (32 to 51 mg kg^{-1}) across all profiles. The highest Li contents occur in soils on the raised platforms at Byers, with values increasing from the hillslope to the bottomslope (43-51 mg kg^{-1}, respectively) and in these sites sedimentary alluminosilicates are abundant.

The trace elements Cu, Cr, Co and Ni are below 7 mg kg^{-1}. They range between 1.6 mg kg^{-1} (Ni in B5) and 6.5 mg kg^{-1} (Cr in B4). All of them show little variation and not special patterns were observed. Cadmium was not detected in any of the profiles. The major and trace elements concentrations generally fall within the range for soils developed on similar parent materials (Kabata-Pendias and Pendias 2001), although some values of Ba and Pb are quite high.

Figures 7 and 8 present the depth distribution of the major and trace elements in the soil profiles. The distribution of Fe and Al show high parallelism in all Byers profiles, whereas this is not as marked in Hurd profiles. The Ca distribution seems to match the depth distributions of Fe and Al, but especially that of Al, although deviations are observed in H4 and B1, B2 and B3, in the latter due to presence of calcite at deeper layers. The Na depth distribution coincides with that of Ca in B3 and H4, but in general is similar to that of Fe and Al, apart from profiles B2, B4 and B6.

The down profile distribution of K is in general quite uniform, the peaks encountered at deep layers in B5 and H4 are related to soil mineralogy (feldspars and sheet silicates). Together with Mg they are in the same concentration range but with opposite distributions at some depth intervals as in B2, B5, B6, B7 and in H1, H2. However, parallelism between K and Mg occurs in B3, B4 and H3. The distribution of Mn is uniform in most soil profiles. However, in B2 and B3 high variation is observed. The down profile distribution of Ba is highly variable, all profiles display peaks at different depth intervals indicating that Ba variations are closely related to mineralogy. The Pb depth profiles show different patterns, uniformity is quite general in soils on the Byers raised platforms and in profiles H1, H2 at Hurd Peninsula. However, variations are observed in the remaining profiles especially in H4. The Sr depth profiles show some variations with depth but without any clear trend. In B1 and H4 peaks are more marked than in other profiles but in B2 Sr is depleted. These irregular variations are also associated with changes in mineralogy. The Zn distribution is quite uniform in all soil profiles. However, increases at deeper layers in B6 and especially in H4 are coincidental with K.

Lithium is the element that shows the more uniform depth distribution in all profiles, in contraposition with this uniformity, Wells and Whitton (1972) indicate that Li presents high variability in soils following the general trends of soil solution circulation. The distribution of Co, Ni, Cu and Cr is quite coincidental in most soil profiles However, more irregular patterns are observed in beach profiles and on the volcanic plugs at Byers Peninsula.

In the studied profiles the relationships between soil properties and chemical elements are analysed through correlations. Significant negative correlations are found between pH and K ext ($r = -0.720$), Na ($r = -0.634$) and sand ($r = -0.626$), whereas pH is directly correlated with Co ($r = 0.581$) and Cr ($r = 0.544$) and with silt ($r = 0.626$) and clay ($r = 0.605$). The carbonate is only positively correlated with Ca ($r = 0.675$). As expected, the organic matter and soil nutrients (TOC and N) are highly correlated ($r = 0.938$), besides organic matter and TOC are directly correlated with Sr ($r = 0.583$) and Cu ($r = 0.529$). The extractable P correlates with Li ($r = 0.561$), K ($r = 0.688$) and clay ($r = 0.555$), indicating their association with the finest soil fraction. The K ext is negatively related to Pb ($r = - 0.607$), Co ($r = - 0.770$) and to silt and clay fractions ($r = - 0.632$ and -0.590, respectively) whereas it is directly related to sand ($r = 0.627$)

and Na (r = 0.610). The sand content is negatively related to silt and clay (r = - 0.997, - 0.973, respectively), Pb (r = -0.915), Li (r = -0.873) and Co (r = - 0.650) and is only positively related with Na (r = 0.609) and Ba (r = 0.613). However, the fine fractions, silt and clay, that are significantly related between them (r = 0.953), show opposite relationships. Thus, negative correlations were found between silt and clay with Na (r = -0.600 and r = -0.616, respectively) and Ba (r = -0.616 and r = -0.585, respectively) and positive with Pb (r = 0.908 and 0.869, respectively), Li (r = 0.855 and r = 0.902, respectively) and Co (r = 0.915 and r = 0.886, respectively) indicating the association of these elements to the fine soil fractions.

Concerning the relationships between the elements, Mg and Zn do not have any relationship with the studied elements. Sr is only related with Cu (r = 0.597), as well as Ni is only related with Cr (r = 0.524). Al is positively correlated with Fe (r = 0.539) and Cr (r = 0.564). Mn and Ca are directly correlated (0.529). Therefore, although the coefficients are not very high they suggest that all these elements are associated. Different origin seem to have Ba, Pb and Li as indicated by the negative correlations between Ba and those elements (r = - 0.643 and r = - 0.517, respectively), whereas Pb is strongly related with Li (r =0.850), and to a lesser extent with Co (r =0.682), indicating the association of these elements. However, Na has no significant correlations with any element, apart from the negative ones with Pb, Li and Co. Cobalt has positive correlations with Cu (r = 0.528) and Fe (r = 0.504). Potassium correlates negatively with Mn, Co, Fe and Ca indicating a different mineralogical source.

An analysis of variance was performed to identify differences in soil properties and elemental composition in relation with physiographic location, geomorphic unit and bedrocks. Physiographic location do not correlates with most soil properties apart from grain size of the fine fractions, EC and extractable K (Table 6). The geomorphic unit is related to more variables, in addition to grain size, EC and exrtractable K, the pH, TOC, OM and N. Furthermore, most soil properties were correlated with the bedrock type, except carbonate and extractable P and the grain size fractions >12.5 mm and <2 mm. The physiographic location and the geomorphic unit are related with fewer elements than the bedrock types that influence the variations of 13 of the total 16 elements analysed, apart from K, Mn and Fe.

Therefore, as bedrock appears to be the main factor of variation for most variables, descriptive statistics were calculated for soil properties as a function of the bedrock type (Table 7). The pH of soils on volcanic, mudstones and greywackes were similar and significantly different from the pH of soils on gravels. Similar TOC, OM and N values are found on three of the bedrocks apart from the gravel greywackes and volcanic rocks. No differences in CO_3 and extractable P among the bedrocks were found whereas extractable K significantly differs between the bedrock types. The largest differences in grain size occur in the fraction 2 - 6.3 mm, and in the sand, silt and clay fractions with differences between mudstones and volcanic rocks in comparison with the other three bedrock types.

According to the descriptive statistics calculated for the elemental composition (Table 7) Mg, K, Zn, Mn, and Fe are similar in the soils on all bedrock types. The Na, Pb, and Ba contents in soils on the mudstones differ significantly from those on the rest of bedrocks. The Sr content on the gravel greywackes is significantly different from the contents on the mudstones and volcanic rocks. The Li content is similar on gravels and greywackes and differs from the contents on mudstones and volcanic rocks. The Co content is similar on gravel greywackes, greywackes and volcanic rocks. The Ni content is similar on gravel mudstones and mudstones and differs from the rest. The Cu content is similar on gravel greywackes, greywackes and volcanic rocks. The Cr content in soils on the volcanic rocks differs from the rest of bedrocks apart from mudstones. The Al content is highest on the volcanic rocks and different from the rest of bedrocks apart from the gravel greywackes. The highest difference in the Ca content is found between the soils on gravel greywackes and on gravel mudstones. Therefore, it appears that the geochemical variability of these soils is in close relation with the parent materials and their mineralogical composition.

4. Discussion

Our results indicate that there are differences in the general soil properties as well as in the elemental and mineralogical composition among the distinctive environments that conforms the soils developed on different bedrocks, geomorphic units and platforms in Byers and Hurd peninsulas. Some of the variations in soil properties may be affected by water movement, thus Navas et al. (2005) found some transfer of highly mobile ^{238}U within a soil profile at a bottomslope in Byers, due to increasing water circulation from the headwaters to the bottomslope and accumulation of ^{238}U at the lower position. Permafrost and the active layer may impact on the underground water recharge and flow in Byers Peninsula (Cuchi et al., 2004).

According to Hall (1997) moisture is the main limitation on freeze-thaw weathering. In the peninsulas continuous permafrost occurs above 30 m a.s.l. and below this altitude, the presence of permafrost is discontinous. Permafrost is found at depths between 25 and 75 cm. Therefore, altitude and topography are main factors affecting the spatial distribution of permafrost. Close to the sea level, permafrost is in general unexisting thus facilitating leaching processes.

Hall (1992) indicates that in Byers Peninsula wetting and drying, salt weathering and chemical weathering could be more important than freeze-thaw. Although Kelly and Zumberge (1961) suggested that in Antarctica the chemical weathering does not causes major changes in the rocks, in the moistest and warmer climate existing in the studied peninsulas some soil processes as leaching occur. However leaching may be limited due to restricted water circulation just during summer periods (Keys and Williams,1981; Blume et al., 1997). Beyer et al. (2000) suggest that although reactions are probably slow in Antarctic conditions, chemical weathering plays a role in areas of maritime Antarctica, parts of the Antarctic Peninsula and the offshore islands.

In general, the soils in Byers and Hurd peninsulas are influenced by the availability of water during the summer. However, due to its warmer climate greater quantities of water are available in this region in comparison with other Antarctic areas. Cryoturbation occurs only during the approximately three months without snow cover during summer. As a consequence of the climatic and physiographic characteristics in this environment, the soils are weakly developed with poor horizon differentiation. In agreement with other studies in King George Island (Jie et al. 2000), poorly developed soils are expected in areas with patterned ground and freeze-thaw cycles, this is generally accepted and has also been observed in Fildes Peninsula. The role of freeze-thaw, wetting and drying, and other weathering mechanisms has also been studied by several authors (Hall 1993; Serrano et al. 1996). In Antartic environments freeze-thaw weathering is recognized to be the most important process causing rock disintegration. In maritime Antarctica, moist conditions may favour chemical weathering in the soil forming process, however, in the soils in this study the geomorphologic (cryogenic) and physical processes, such as soil movement, were of greater importance. The soils in the Byers and Hurd peninsulas are different from the soils described by Bockheim and McLeod (2006) in the Wright Valley (Dry Valleys, Antarctica) which are on much older surfaces and are characterized by varying contents of soluble salts and degrees of chemical weathering.

5. Conclusions

In the soil profiles studied at Byers and Hurd peninsulas, the main influences on soil development and evolution are physical weathering processes related to cryogenic processes resulting from freeze-thaw cycles. The cryogenic processes lead to rock disintegration and supply the material for soil development. The different characteristics of bedrocks in the Byers and Hurd peninsulas influence the mineralogical composition of the soils as well as the grain size distribution and the carbonate content. The scarcity of vegetation cover is linked to the low contents of organic matter and TOC, although relatively high OM contents are related with the abundance of mosses. Nutrients such as N, K and P concentrations are low except in the soils that receive seabird inputs especially those on the beaches.

According to the mineralogical composition which is dominated by non clay silicate minerals, the soils of Hurd Peninsula appear to be compositionally more immature than those at Byers Peninsula. The soils in Byers Peninsula contain abundance of sheet silicates although with no transformations to suggest a more intense weathering. The elemental composition of the soils is strongly related to the mineralogy of the parent materials. Therefore, chemical weathering appears to be of minor relevance in comparison with physical weathering.

Leaching and other weathering processes, although limited in extent affect the evolution of the soils, particularly in relation to water movement down the soil profile. The absence of salts in the soils of the beaches supports the existence of leaching. In addition, acid pH values are only found in soils of the beaches, possibly due to more intense leaching as a result of the higher water circulation in the lowlands. However, these processes seem to be of more limited effect because of the short period of water circulation that occurs only during the summer. Permafrost, in combination with freezing-thaw cycles and active layer and wetting-drying processes, also plays an important role in weathering mechanisms. Further research to clarify the role of permafrost and the active layer is needed and especial attention must be given to variations under changing climatic conditions.

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FIGURE CAPTIONS

Figure 1. Location and geology of Byers and Hurd peninsulas

Figure 2. Geomorphological setting of Byers Peninsula and position of the sampling sites.

Figure 3. Geomorphological setting of Hurd Peninsula and position of the sampling sites.

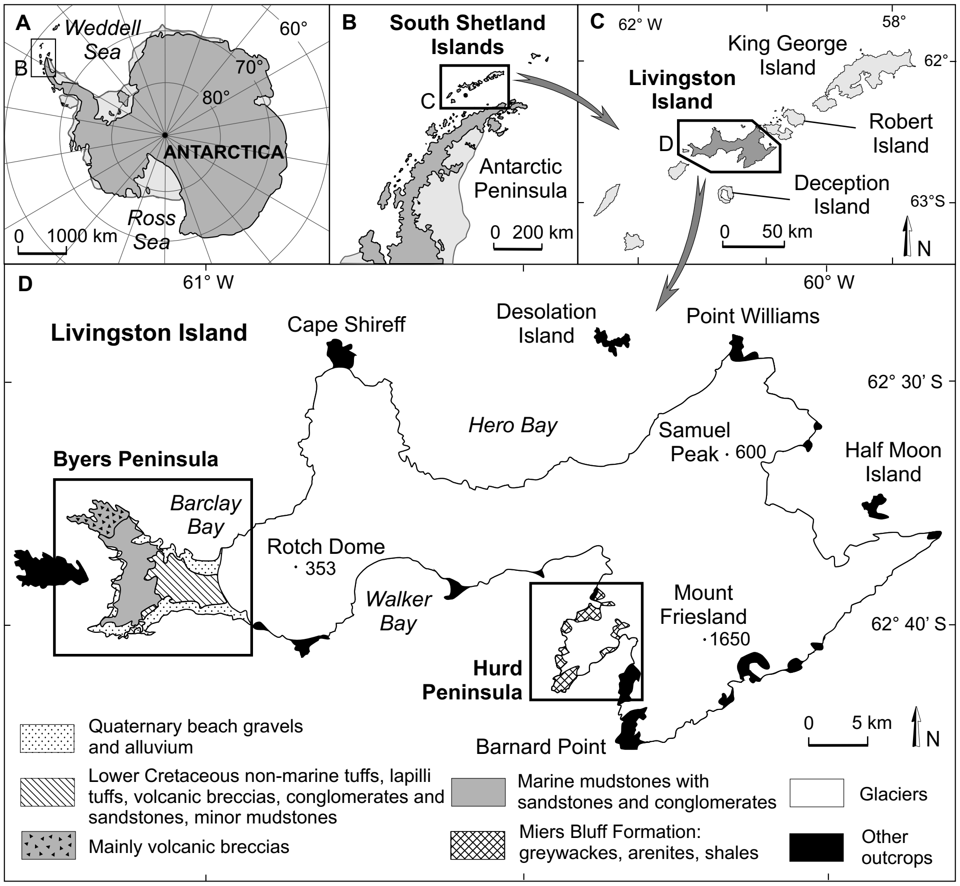
Figure 4. Distribution of grain size fractions in the soil depth profiles of Byers and Hurd peninsulas.

Fig. 5. Mineralogical composition in the soil depth profiles of Byers and Hurd peninsulas.

Figure 6. Average values and standard deviation of the elemental composition in the soil profiles of Byers and Hurd peninsulas.

Figure 7. Elemental composition in the soil depth profiles from Byers Peninsula.

Figure 8. Elemental composition in the soil depth profiles from Hurd Peninsula



A
Weddell Sea
60°
70°
80°
B
ANTARCTICA
Ross Sea
0 1000 km
B
South Shetland Islands
C
Antarctic Peninsula
0 200 km
C
62° W
58°
King George Island
62°
Livingston Island
Robert Island
D
Deception Island
63°S
0 50 km
N
D
61° W
60° W
Livingston Island
Cape Shireff
Desolation Island
Point Williams
62° 30' S
Hero Bay
Samuel Peak · 600
Half Moon Island
Byers Peninsula
Barclay Bay
Rotch Dome · 353
Walker Bay
Mount Friesland ·1650
62° 40' S
Hurd Peninsula
Barnard Point
0 5 km
N
Quaternary beach gravels and alluvium
Lower Cretaceous non-marine tuffs, lapilli tuffs, volcanic breccias, conglomerates and sandstones, minor mudstones
Mainly volcanic breccias
Marine mudstones with sandstones and conglomerates
Miers Bluff Formation: greywackes, arenites, shales
Glaciers
Other outcrops

Fig. 1

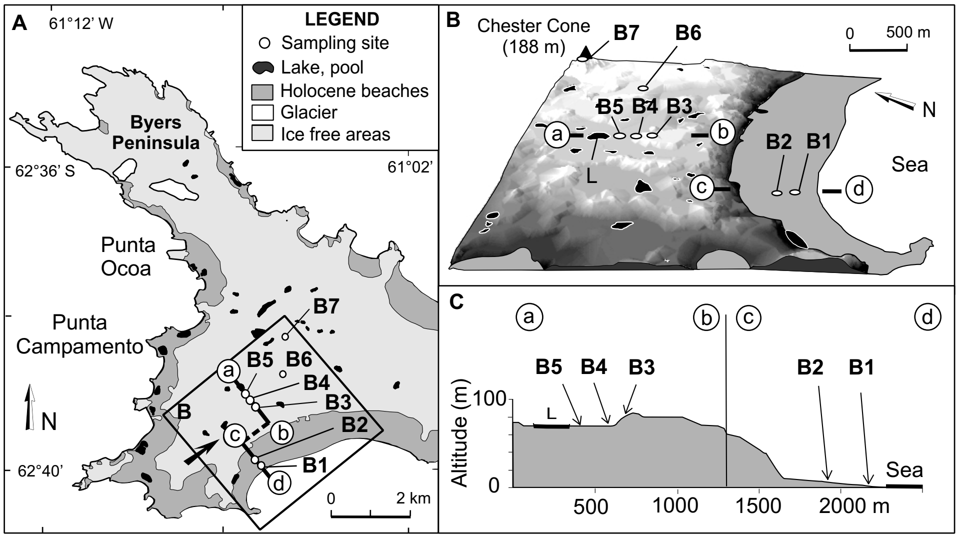
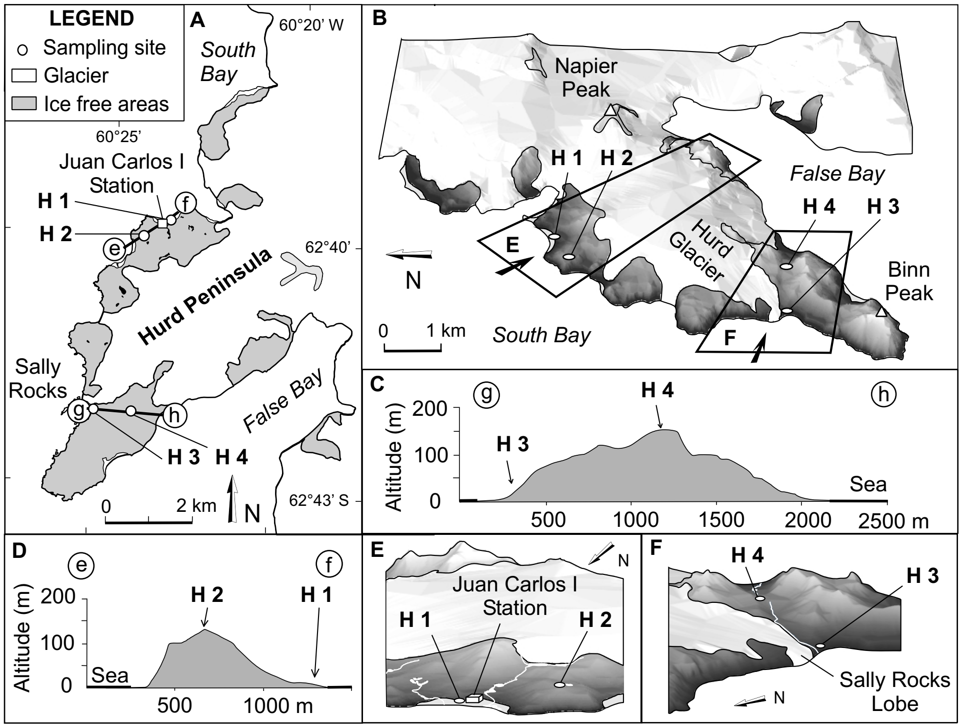

A
61°12' W
LEGEND
Sampling site
Lake, pool
Holocene beaches
Glacier
Ice free areas
Byers Peninsula
62°36' S
61°02'
Punta Ocoa
Punta Campamento
B7
B5
B6
B4
B3
B2
B1
B
N
62°40'
0
2 km
B
Chester Cone (188 m)
B7
B6
0
500 m
B5
B4
B3
N
B2
B1
Sea
L
C
Altitude (m)
100
0
L
B5
B4
B3
B2
B1
Sea
500
1000
1500
2000 m

Fig. 2



LEGEND
Sampling site
Glacier
Ice free areas
A
60°20' W
South Bay
60°25'
Juan Carlos I Station
H 1
H 2
62°40'
Hurd Peninsula
Sally Rocks
False Bay
H 3
H 4
0
2 km
N
62°43' S
B
Napier Peak
False Bay
Hurd Glacier
Binn Peak
South Bay
0
1 km
E
F
C
Altitude (m)
200
100
0
Sea
500
1000
1500
2000
2500 m
D
Sea
1000 m
Juan Carlos I Station
Sally Rocks Lobe

Fig. 3

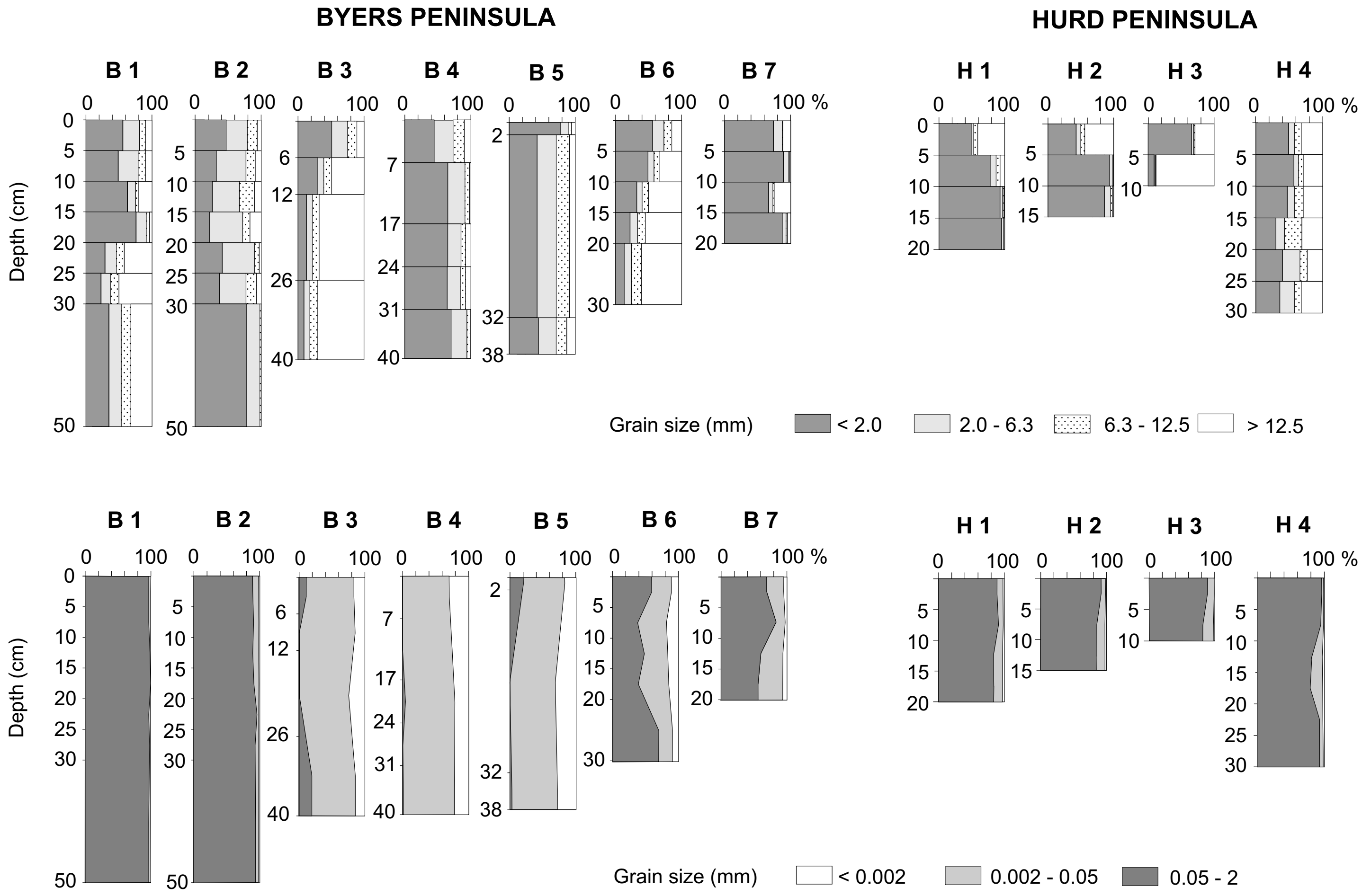

BYERS PENINSULA
HURD PENINSULA
B 1
B 2
B 3
B 4
B 5
B 6
B 7
H 1
H 2
H 3
H 4
Depth (cm)
100 %
Grain size (mm)
< 2.0
2.0 - 6.3
6.3 - 12.5
> 12.5
Grain size (mm)
< 0.002
0.002 - 0.05
0.05 - 2

Fig. 4

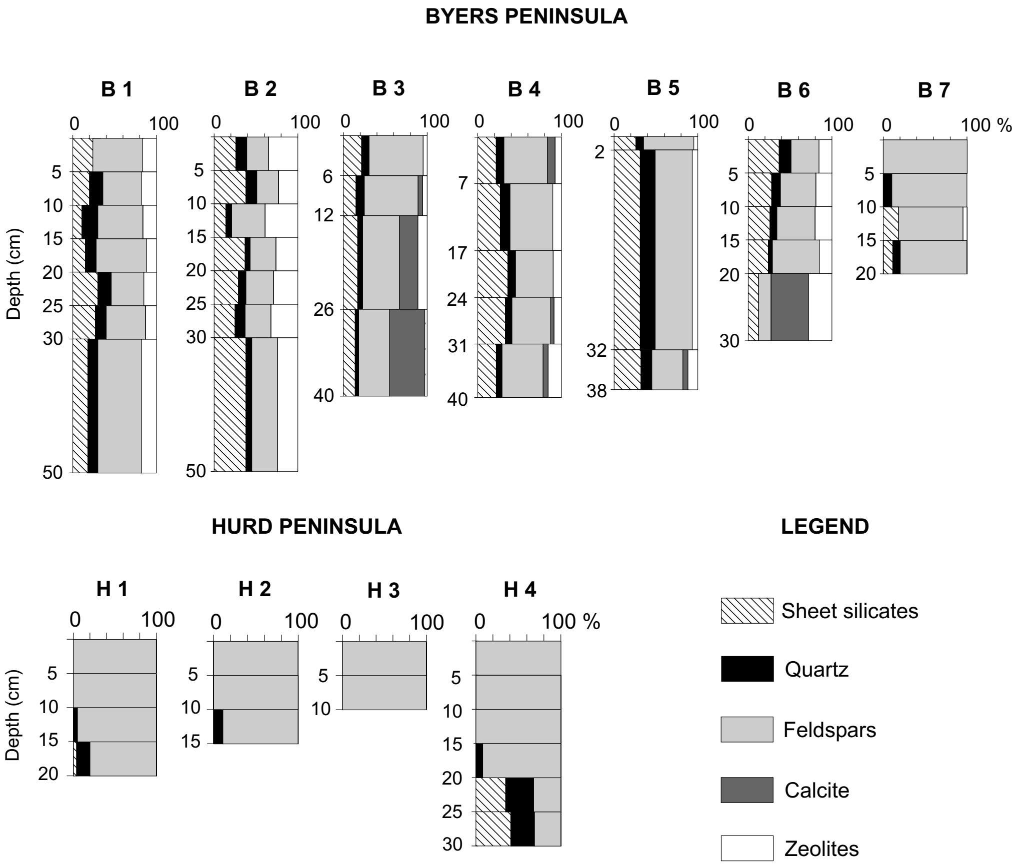
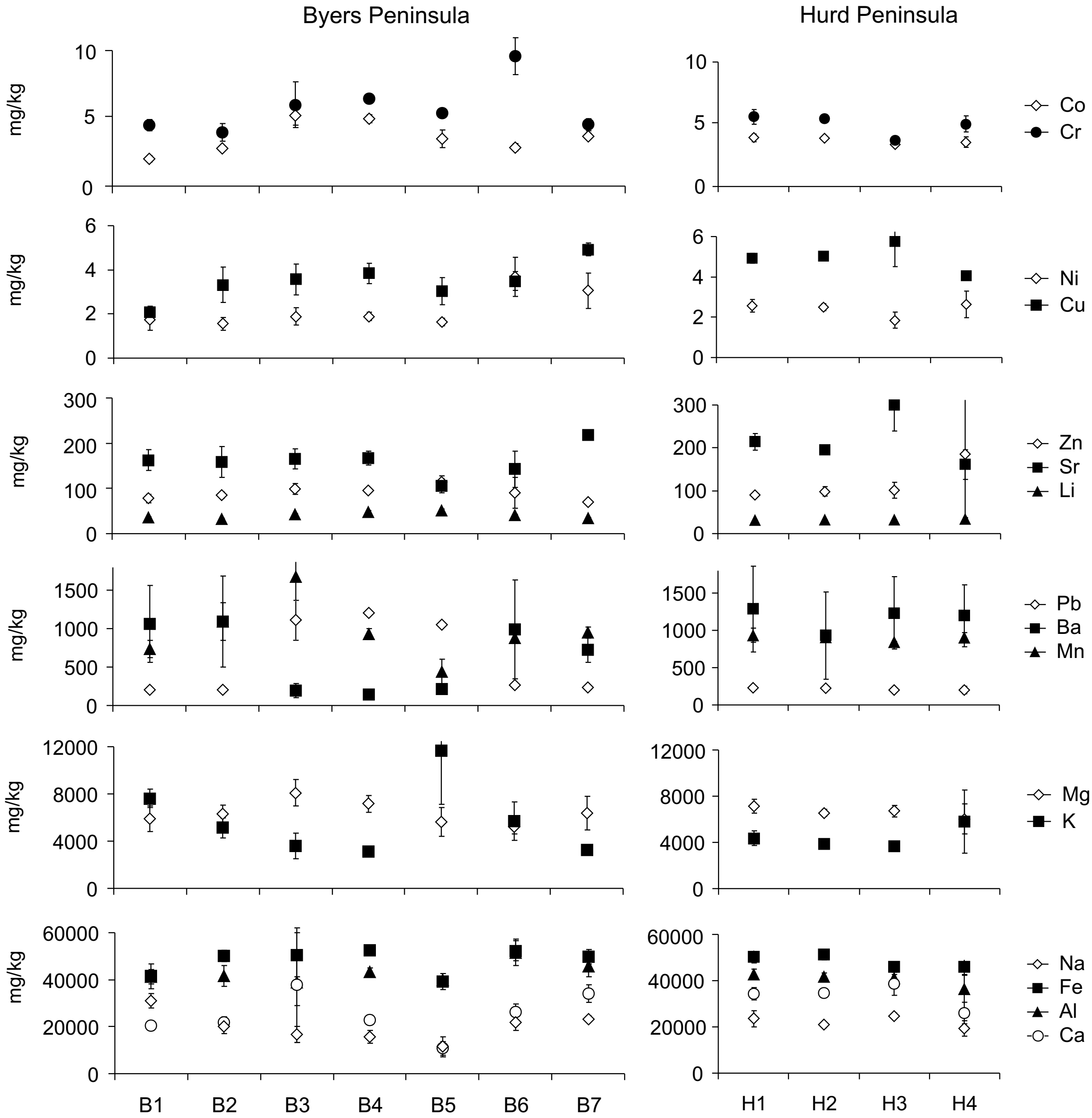

BYERS PENINSULA
B 1
B 2
B 3
B 4
B 5
B 6
B 7
0
100
100 %
Depth (cm)
HURD PENINSULA
H 1
H 2
H 3
H 4
LEGEND
Sheet silicates
Quartz
Feldspars
Calcite
Zeolites

Fig. 5



Byers Peninsula
Hurd Peninsula
mg/kg
10
5
0
Co
Cr
6
4
2
Ni
Cu
300
200
100
Zn
Sr
Li
1500
1000
500
Pb
Ba
Mn
12000
8000
4000
Mg
K
60000
40000
20000
Na
Fe
Al
Ca
B1
B2
B3
B4
B5
B6
B7
H1
H2
H3
H4

Fig 6

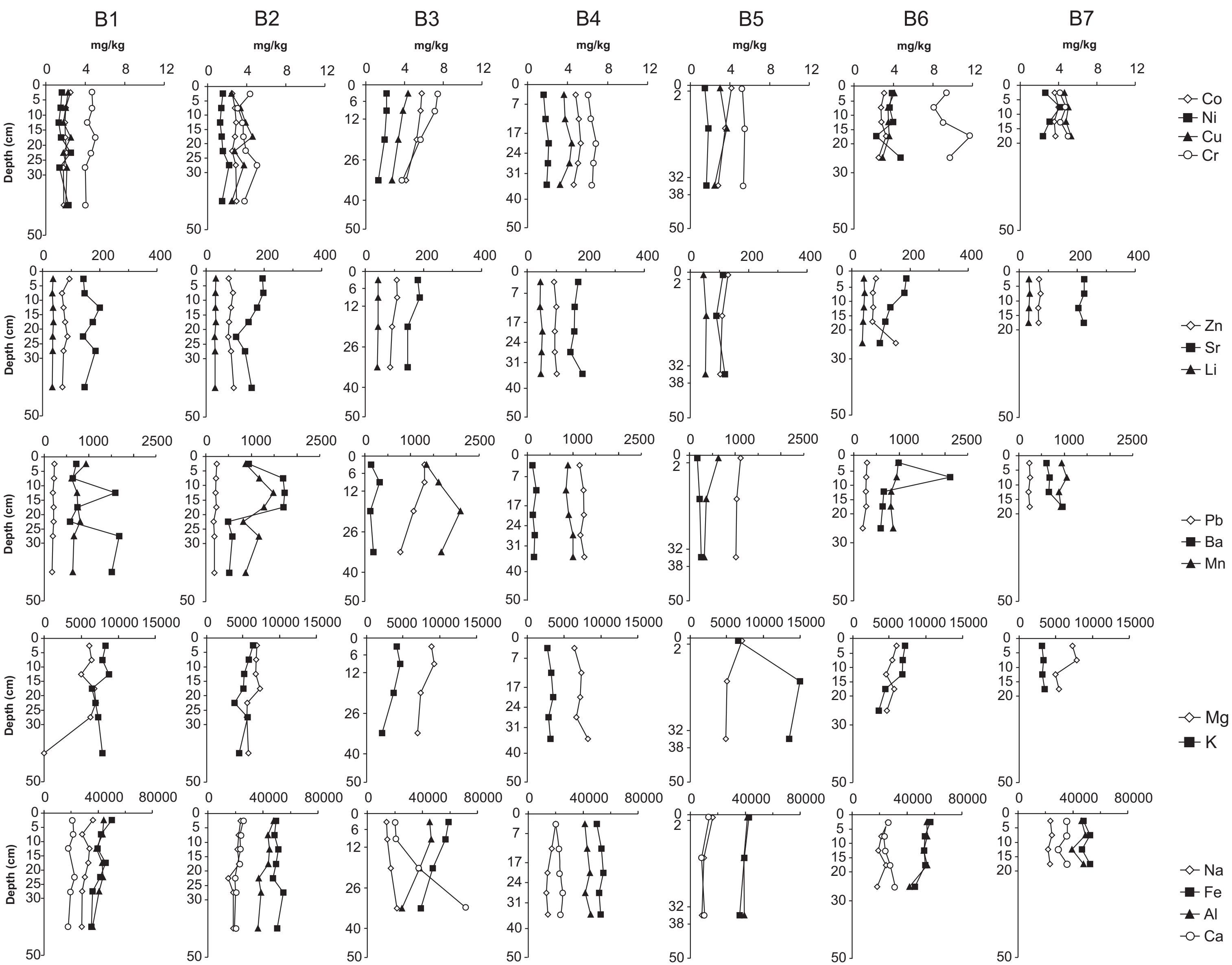
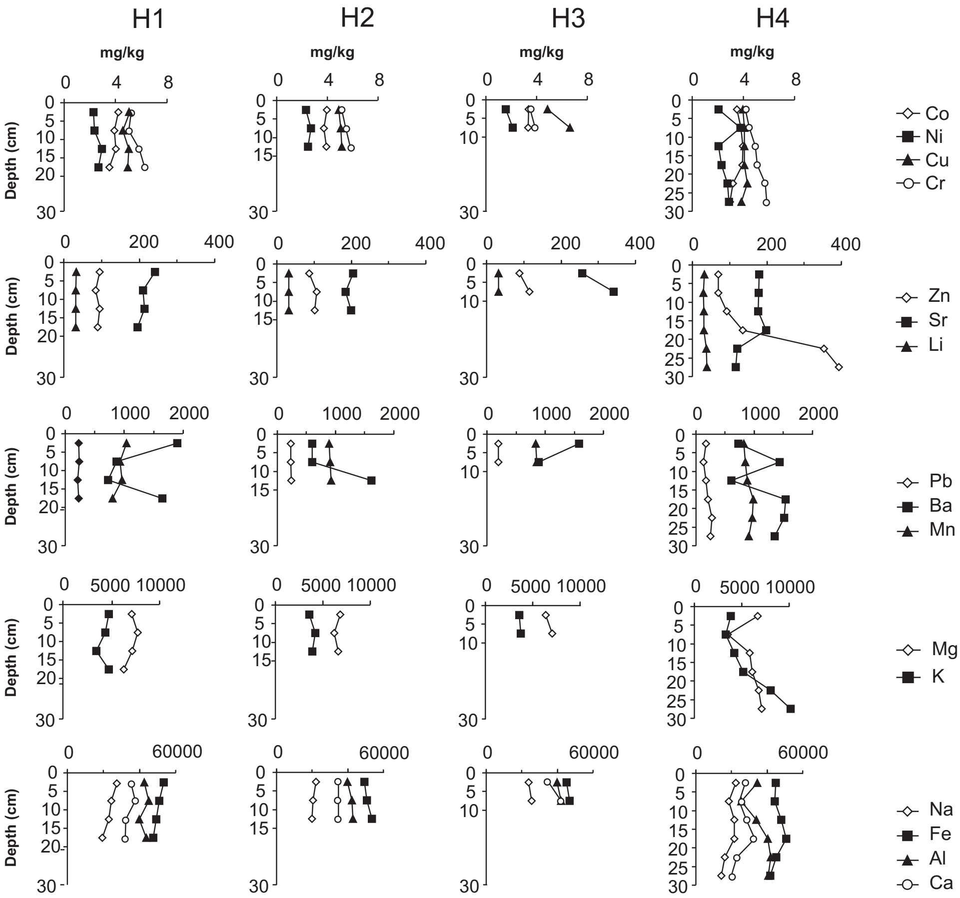

B1
B2
B3
B4
B5
B6
B7
mg/kg
Depth (cm)
Co
Ni
Cu
Cr
Zn
Sr
Li
Pb
Ba
Mn
Mg
K
Na
Fe
Al
Ca

Fig 7



H1
H2
H3
H4
mg/kg
Depth (cm)
Co
Ni
Cu
Cr
Zn
Sr
Li
Pb
Ba
Mn
Mg
K
Na
Fe
Al
Ca

Fig 8

Table 1. Physiographic and lithological characteristics of the soils at the sampling sites of Byers and Hurd peninsulas

Peninsula	sampling sites	geomorphological position	altitude m	bedrock
	B1	raised beach	7	gravels
	B2	raised beach	10-11	sand & gravels
	B3	raised platform	88	mudstones, sandstones
Byers	B4	raised platform	80	mudstones, sandstones
	B5	raised platform	72	mudstones, sandstones
	B6	volcanic plug	108	andesitic basalts
	B7	volcanic plug	188	andesitic basalts
	H1	raised beach	5	gravels
Hurd	H2	platform	125	greywackes, arenites
	H3	raised beach	6	gravels
	H4	platform	155	greywackes, arenites

Table 2. Depth distribution of the main soil properties in the profiles of Byers and Hurd peninsulas

Sample	Depth cm	colour moist	colour dry	pH	EC dSm^{-1}	CO_3 %	OM %	TOC %	T N %	P ext mg /100 g	K ext $mg\ kg^{-1}$
Byers Peninsula											
B 1	0-5	10YR 3/3	10YR 5/3	4,6	0,12	0,12	0,62	0,36	0,05	1,4	395,0
B 1	5-10	10YR 3/3	10YR 5/3	4,5	0,07	0,09	0,50	0,29	0,02	1,0	269,0
B 1	10-15	10YR 3/3	10YR 5/3	4,6	0,05	0,06	0,42	0,24	0,03	0,7	275,0
B 1	15-20	10YR 3/3	10YR 5/3	5,2	0,04	0,00	0,19	0,11	0,02	0,6	253,0
B 1	20-25	7.5YR 2.5/1.5	7.5YR 4.5/4	6,2	0,04	0,00	0,17	0,10	0,01	1,4	277,0
B 1	25-30	7.5YR 2.5/1.5	7.5YR 4.5/4	6,6	0,05	0,06	0,26	0,15	0,02	1,1	302,0
B 1	30-50	10YR 2.5/3	10YR 5/2	6,6	0,06	0,17	0,56	0,33	0,03	1,0	328,0
B2	0-5	10YR 3/3	10YR 5/3	5,0	0,08	0,04	0,84	0,49	0,06	1,8	288,0
B2	5-10	10YR 3/3	10YR 5/3	5,3	0,05	0,00	0,66	0,38	0,02	2,0	289,0
B2	10-15	10YR 3/3	10YR 5/3	5,8	0,03	0,18	0,53	0,31	0,02	1,7	338,0
B2	15-20	10YR 3/3	10YR 5/3	5,7	0,03	0,00	0,65	0,38	0,02	1,6	330,0
B2	20-25	7.5YR 3/1.5	7.5YR 4/3.5	6,0	0,03	0,23	0,30	0,18	0,01	0,7	301,0
B2	25-30	7.5YR 3/1.5	7.5YR 4/3.5	6,1	0,03	0,32	0,26	0,15	0,01	1,3	288,0
B2	30-50	10YR 3.5/3	10YR 5/3	6,5	0,03	0,13	0,24	0,14	0,01	1,0	214,0
B 3	0-6	7.5YR 4.5/4	7.5YR 3.5/2	8,0	0,09	0,12	0,97	0,56	0,03	2,9	51,6
B 3	6-12	7.5YR 4.5/4	7.5YR 3/2	7,8	0,14	0,27	0,98	0,57	0,02	3,4	
B 3	12-26	7.5YR 5.5/4	7.5YR 3/3	8,3	0,13	6,64	0,54	0,31	0,01	0,9	40,1
B 3	26-39	10YR 5.5/4	10YR 3/3	8,6	0,11	19,27	0,41	0,24	0,01	0,6	32,5
B 4	0-7	10YR 5/3	10YR 3/3	8,2	0,13	0,82	0,81	0,47	0,09	1,8	39,1
B 4	7-17	10YR 5/4	10YR 2/2	7,7	0,11	0,00	0,97	0,56	0,02	8,4	38,7
B 4	17-24	10YR 4.5/6	10YR 3/4	7,6	0,14	0,41	0,92	0,54	0,03	0,8	39,7
B 4	24-31	10YR 5.5/4.5	10YR 3.5/3	8,4	0,11	0,54	0,54	0,31	0,02	0,3	37,8
B 4	31-39	10YR 5.5/4	10YR 3/3	8,1	0,14	0,68	1,01	0,58	0,01	3,6	40,3
B 5	0-2	5Y 5/3	5Y 3/2	7,8	0,06	0,06	0,84	0,48	0,02	1,8	43,9
B 5	2-32	10YR 5/3	10YR 4/3.5	7,9	0,05	0,06	1,27	0,74	0,03	52,0	47,4
B 5	32-38	10YR 5/3	10YR 3/2	8,1	0,06	0,12	1,29	0,75	0,03	40,8	49,7
B 6	0-5	10YR 4/3	10YR 4.5/4	7,8	0,12	0,27	0,83	0,48	0,01	4,0	223,0
B 6	5-10	10YR 4/3	10YR 4.5/3.5	7,9	0,12	0,25	0,99	0,57	0,06	5,6	228,0
B 6	10-15	10YR 4/3	10YR 5/3.5	8,1	0,13	0,39	0,82	0,48	0,02	5,4	189,0
B 6	15-20	10YR 3.5/3	10YR 5/4	8,3	0,15	0,23	0,53	0,31	0,02	5,8	115,0
B 6	20-30	10YR 2.5/1	10Y 4.5/4	8,2	0,23	5,34	0,51	0,30	0,02	1,1	87,6
B 7	0-5	10YR 3/3.5	10YR 4.5/4	6,9	0,09	0,00	2,60	1,51	0,13	0,0	113,0
B 7	5-10	10YR 3/3.5	10YR 4.5/4	7,1	0,08	0,04	2,77	1,61	0,14	0,1	141,0
B 7	10-15	10YR 3/3.5	10YR 4.5/4	7,3	0,08	0,16	2,61	1,51	0,15	0,1	182,0
B 7	15-20	10YR 3/3.5	10YR 4.5/4	7,2	0,09	0,17	2,79	1,62	0,14	0,0	175,0
Hurd Peninsula											
H 1	0-5	10YR 2/2	10YR 4.5/2	6,5	0,03	0,00	0,55	0,32	0,01	0,7	78,1
H 1	5-10	10YR 2/2	10YR 4.5/2	7,2	0,03	0,01	0,63	0,37	0,03	0,5	85,6
H 1	10-15	10YR 2/2	10YR 4.5/2	7,4	0,03	0,05	1,05	0,61	0,04	0,4	95,2
H 1	15-20	10YR 2/2	10YR 4.5/2	7,3	0,03	0,01	1,32	0,76	0,04	0,3	97,3
H 2	0-5	7.5YR 3/2	7.5YR 4.5/4	6,8	0,05	0,00	0,67	0,39	0,03	0,2	83,0
H 2	5-10	7.5YR 3/2	7.5YR 4.5/4	7,1	0,03	0,00	0,67	0,39	0,02	0,0	93,7
H 2	10-15	7.5YR 3/2	7.5YR 4.5/4	7,1	0,03	0,00	0,81	0,47	0,04	0,0	113,0
H 3	0-5	10YR 2.5/2.5	10YR 4/3	4,9	0,15	0,00	4,56	2,65	0,25	5,4	126,0
H 3	5-10	10YR 2.5/2.5	10YR 4.5/3	5,2	0,15	0,25	3,23	1,87	0,24	8,9	147,0
H 4	0-5	10YR 2.5/1	10YR 3.5/1	7,7	0,04	0,07	0,16	0,09	0,01	0,0	102,0
H 4	5-10	10YR 2.5/1	10YR 3.5/1	7,7	0,04	0,14	0,16	0,10	0,01	0,0	130,0
H 4	10-15	10YR 2.5/1	10YR 3.5/1	8,2	0,04	0,00	0,18	0,11	0,01	0,2	151,0
H 4	15-20	10YR 2.5/1	10YR 3.5/1	8,0	0,05	0,47	0,33	0,19	0,01	0,3	174,0
H 4	20-25	10YR 3.5/2	10YR 5/2	8,2	0,04	0,23	0,51	0,29	0,02	0,4	79,8
H 4	25-30	10YR 3.5/2	10YR 5/2	7,9	0,05	0,00	0,50	0,29	0,03	0,4	81,6

Table 3. Summary statistics of the properties of the soils of Byers and Hurd peninsulas.

	BYERS PENINSULA					HURD PENINSULA				
	mean	sd	min	max	CV %	mean	sd	min	max	CV %
pH	7.2	1.2	5.5	8.2	16	6.8	1.2	5.1	7.9	18
EC dSm^{-1}	0.1	0.0	0.0	0.1	46	0.1	0.1	0.0	0.1	88
CO_3 %	1.2	2.4	0.1	6.6	192	0.1	0.1	0.0	0.2	103
TOC %	0.6	0.5	0.2	1.6	78	0.8	1.0	0.2	2.3	113
OM %	1.0	0.8	0.4	2.7	78	1.5	1.6	0.3	3.9	114
N %	0.0	0.0	0.0	0.1	104	0.1	0.1	0.0	0.2	140
K ext mg kg^{-1}	147.3	115.6	31.1	299.9	79	110.5	21.7	89.1	136.5	20
P ext g/100 g	61.9	112.6	0.3	315.3	182	19.8	34.5	0.5	71.4	175
Sand %	46.1	41.1	1.1	97.3	89	87.3	1.9	85.1	89.7	2
Silt %	41.5	31.3	2.1	75.5	75	10.6	1.9	8.5	13.1	18
Clay %	12.4	10.2	0.6	25.4	82	2.1	0.4	1.8	2.6	17

n = 35 Byers Peninsula

n = 15 Hurd Peninsula

Table 4 Summary statistics of the mineralogical composition of soils from Byers and Hurd peninsulas

		Sheet silicates*		Quartz		Feldspars		Calcite		Zeolites	
						%					
Profile ID	**n**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
BYERS											
B7	4	7.3	4.9	4.8	0.7	86.8	10.4	nd	-	nd	-
B6	5	25.4	9.0	7.4	3.8	38.6	15.5	9.0	20.1	19.6	5.1
B5	3	29.7	3.2	13.3	4.5	47.0	11.8	2.0	-	8.0	3.6
B4	5	28.4	5.9	8.8	1.9	48.4	2.8	3.8	2.5	10.6	3.1
B3	4	17.3	4.0	7.0	2.6	52.0	13.6	17.5	18.0	6.3	3.4
B2	7	29.6	8.9	9.6	3.0	31.1	4.7	nd	-	29.7	5.9
B1	7	20.7	6.7	14.0	3.3	50.0	6.7	nd	-	15.3	2.3
HURD											
H4	6	38.0	4.2	23.0	13.2	75.8	34.5	nd	-	nd	-
H3	2	nd	-	nd	-	100.0	0.0	nd	-	nd	-
H2	3	nd	-	4.0	-	96.0	6.9	nd	-	nd	-
H1	4	2.0	-	4.3	4.9	93.8	9.5	nd	-	nd	-

* Chlorite, smectite

Table 5. Summary statistics of the elemental composition of the soils from Byers and Hurd peninsulas.

	BYERS PENINSULA					HURD PENINSULA				
Element mg kg^{-1}	mean	sd	min	max	CV %	mean	sd	min	max	CV %
Fe	48010	5374	39247	52503	11	48381	2854	45886	51304	6
Al	43171	4332	38747	51610	10	40413	2917	36181	42782	7
Ca	24882	9000	10782	37732	36	33462	5257	26120	38607	16
Na	20072	6287	11520	31017	31	22090	2528	19191	24758	11
K	5728	3063	3107	11644	54	4429	953	3665	5791	22
Mg	6387	974	5221	8087	15	6605	464	6007	7130	7
Mn	958.7	379.3	439.7	1679.2	40	896.7	38.9	842.1	934.2	4
Ba	635.5	436.7	146.4	1093.6	69	1163.6	154.7	938.3	1285.7	13
Pb	611.2	482.8	202.6	1205.1	79	213.8	18.7	195.2	233.7	9
Sr	160.1	33.5	106.3	218.8	21	218.0	58.6	161.2	299.3	27
Zn	90.2	14.6	69.1	113.7	16	119.3	44.5	91.5	185.8	37
Li	40.6	7.0	32.2	50.7	17	32.2	0.8	31.6	33.3	2
Cr	5.8	1.9	4.0	9.6	33	4.9	0.9	3.7	5.6	18
Cu	3.5	0.9	2.1	4.9	25	4.9	0.7	4.1	5.8	14
Co	3.6	1.2	2.0	5.2	33	3.7	0.3	3.4	3.9	7
Ni	2.2	0.8	1.6	3.7	37	2.4	0.4	1.9	2.6	15
Cd	nd	nd	nd	nd		nd	nd	nd	nd	

n = 35 Byers Peninsula

n = 15 Hurd Peninsula

Table 6. Summary table of the significance for the main factors

Variable		Physiographic location	Geomorphic unit	Bedrock types
Soil properties				
pH		ns	***	***
EC	dSm^{-1}	**	***	***
CO_3	%	ns	ns	ns
TOC	%	ns	**	***
OM	%	ns	*	***
N	%	ns	*	***
P ext	mg/100g	ns	ns	ns
K ext	mg kg^{-1}	**	***	***
>12.5 mm	%	ns	ns	ns
6.3-12.5 mm	%	0.09	ns	**
2.0-6.3 mm	%	***	ns	***
< 2 mm	%	ns	ns	ns
Sand	%	***	***	***
Silt	%	***	***	***
Clay	%	***	***	***
Element mg kg^{-1}				
Mg		ns	ns	**
K		ns	ns	ns
Na		ns	***	***
Pb		***	***	***
Ba		***	***	***
Zn		**	*	**
Sr		***	ns	***
Li		***	***	***
Mn		ns	ns	ns
Co		ns	***	***
Ni		ns	***	***
Cu		***	ns	***
Cr		ns	***	***
Fe		ns	ns	ns
Al		*	***	***
Ca		**	ns	**

ns = non significant, *≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Table 7. Summary statistics of soil properties and elemental composition for the different bedrock types

		Gravel greywackes			Gravel mudstones			Greywackes			Mudstones			Volcanic		
		mean	sd		mean	sd		mean	sd		mean	sd		mean	sd	
Soil properties																
pH		6.4	0.3	a	5.6	0.2	a	7.6	0.2	b	8	0.2	b	7.6	0.2	b
EC	dSm^{-1}	0.1	0	ab	0	0	a	0	0	a	0.1	0	b	0.1	0	b
CO_3	%	0	1.2	a	0.1	0.8	a	0.1	0.9	a	2.4	0.8	a	0.8	0.9	a
TOC	%	1.1	0.2	a	0.2	0.1	b	0.2	0.1	b	0.5	0.1	ab	0.9	0.1	a
OM	%	1.9	0.3	a	0.4	0.2	b	0.4	0.2	b	0.9	0.2	ab	1.6	0.2	a
N	%	0.1	0	a	0	0	b	0	0	b	0	0	b	0.1	0	ba
P ext	mg/100 g	2.7	3.6	a	1.2	2.3	a	0.1	2.9	a	9.8	2.5	a	2.4	2.9	a
K ext	$mg\ kg^{-1}$	104.9	14.7	a	296.2	9.6	b	112	12	ad	41.9	10.8	c	161.5	12	d
>12.5 mm	%	27.6	8.9	a	15.7	5.8	a	24.8	7.3	a	21.2	6.3	a	28.8	7.3	a
6.3-12.5 mm	%	3	2.2	a	11.1	1.4	a	9.7	1.8	a	11	1.6	a	7	1.8	a
2.0-6.3 mm	%	4	3.6	a	29.2	2.4	b	11.8	3	ac	20	2.6	bc	9.5	3	ac
< 2 mm	%	65.4	9.6	a	43.9	6.3	a	53.6	7.8	a	47.7	6.8	a	54.6	7.8	a
Sand	%	86.3	3.4	a	94.5	2.2	a	88.9	2.8	a	4.9	2.4	b	57.8	2.8	c
Silt	%	11.4	2.6	a	4.4	1.7	a	9.1	2.1	a	73	1.8	b	32.8	2.1	c
Clay	%	2.3	1.4	a	1.1	0.9	a	1.9	1.1	a	22.1	1	b	9.4	1.1	c
Element $mg\ kg^{-1}$																
Fe		48896	2270	a	45810	1486	a	47692	1854	a	48536	1605	a	51213	1854	a
Al		42181	1986	ab	41522	1300	a	38024	1621	a	40915	1404	a	48945	1621	b
Ca		35756	3701	a	21101	2423	b	29009	3022	ba	24825	2617	ba	29834	3022	ba
Na		23953	1760	a	25646	1152	a	19748	1437	ab	15004	1244	b	22538	1437	a
K		4128	1054	a	6374	690	a	5161	861	a	5412	745	a	4624	861	a
Mg		6992	437	a	6111	286	a	6193	357	a	7094	309	a	5732	357	a
Mn		903.5	123.7	a	914	81	a	904.4	101	a	1056.8	87.5	a	913.7	101	a
Ba		1268.7	177.6	a	1079.7	116.3	a	1109.9	145	a	179.3	125.6	b	875.1	145	a
Pb		215.3	32.1	a	204.9	21	a	211.8	26.2	a	1137.1	22.7	b	248.5	26.2	a
Sr		243.3	15.3	a	160.8	10	b	172.9	12.5	b	150.9	10.8	b	176.4	12.5	b
Zn		94.9	22.3	a	81.6	14.6	a	156.6	18.2	a	101.4	15.7	a	80.9	18.2	a
Li		32.1	1.3	a	34	0.8	ac	32.7	1	a	46.9	0.9	b	37.8	1	c
Cr		5	0.6	a	4.2	0.4	a	5.2	0.5	a	6	0.4	ab	7.3	0.5	b
Cu		5.2	0.3	a	2.7	0.2	b	4.4	0.2	ac	3.5	0.2	bc	4.1	0.2	ac
Co		3.7	0.2	a	2.4	0.1	b	3.7	0.2	a	4.7	0.2	c	3.3	0.2	a
Ni		2.3	0.2	ab	1.6	0.1	a	2.6	0.2	b	1.8	0.1	a	3.4	0.2	c

* different letters indicate significant differences