**INTERPRETING ENVIRONMENTAL CHANGES FROM
RADIONUCLIDES AND SOIL CHARACTERISTICS IN
DIFFERENT LANDFORM CONTEXTS OF ELEPHANT ISLAND
(MARITIME ANTARCTICA)**

A. Navas¹, E. Serrano², J. López-Martínez³, L. Gaspar¹, I. Lizaga¹

¹Estación Experimental de Aula Dei, EEAD-CSIC. Avenida Montañana 1005, 50059
Zaragoza, Spain. anavas@eead.csic.es, l.gaspar@eead.csic.es, ilizaga@eead.csic.es

² Departamento de Geografía, Universidad de Valladolid, 47011, Valladolid, Spain.
serrano@fyl.uva.es

³Departamento de Geología y Geoquímica, Facultad de Ciencias, Universidad
Autónoma de Madrid, 28049 Madrid. Spain. jeronimo.lopez@uam.es

ABSTRACT

Soils in ice-free areas of Elephant Island (South Shetland Islands) have been forming since the last deglaciation following the glacial retreat that started in the area probably later than 9.7-5.5ka. In paraglacial landscapes landforms and processes in transition from glacial to non-glacial conditions, are experiencing rapid environmental adjustments under conditions of climate change. Soils are highly sensitive and can be good descriptors of these transitional changes. A soil sampling campaign was undertaken for characterizing soils developed on moraines and marine platforms, underlain by metamorphic rocks and with distinctive periglacial features. Eight soil profiles were sampled to investigate the processes involved in their development and the relations with main landforms and processes of ice retreat. The stony Cryosols with mosses and lichens coverage are developed in permafrost environment with an active layer depth of 15-150 cm. Soil organic C content (0.16–1.6%) and large variations of P, K and N contents are related to ornithogenic activity. Soils on moraines and platforms show differences that reflect the more recent exposure of moraines that preserve most the characteristics of the parent material. More vegetated soils on platforms show ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ activities (11 and 25 Bq kg⁻¹, respectively) at the topsoil whereas absence of ^{137}Cs and depleted levels of $^{210}\text{Pb}_{\text{ex}}$ occurred in more recently exposed and less developed soils on moraines. Fallout radionuclides are good tracers for identifying characteristics of soil development and providing information on environmental changes of interest to understand the soil response to actual changes in unstable paraglacial environments.

KEY WORDS: Soils and Geomorphology, Geochemistry, Radionuclides, Moraines and Platforms, West Antarctica

INTRODUCTION

In ice-free environments of maritime Antarctica accelerated changes, such as permafrost degradation and variations in active layer thickness (Oliva et al., 2017a, b), are affecting the dynamics of terrestrial ecosystems and also influencing soil formation (Bockheim et al., 2013; Navas et al., 2017). Beyond glaciers paraglacial environments are unstable systems in transition from glacial to non-glacial conditions. Paraglacial landscapes are highly dynamic following adjustment processes after glacier retreat. A close interaction between geomorphological characteristics of recently deglaciated surfaces and climate has been described as playing a key role in soil features of ice-free areas (Balks et al., 2013; Michel et al., 2014; Turner et al., 2016).

Soils in ice-free areas of Elephant Island have been forming since the last glacial retreat in a maritime warmer climate that is wetter than in inner continental Antarctica. These more favourable moist and temperature conditions are fundamental to soil development in the region (Bockheim, 2015); in addition to physical rock disintegration, environmental conditions promote chemical weathering of the substrate (Campbell and Claridge, 1987) with different degrees of intensity depending on the thermal and moisture regimes. A variety of periglacial, and paraglacial alluvial and slope processes and related landforms have been described in ice-free areas of the South Shetland Islands (e.g. López-Martínez et al., 2012, 2016; Oliva and Ruiz-Fernández, 2015) and the close interaction between permafrost and cryoturbation processes have generated patterned ground terrain (Serrano et al., 2008, 2010; Ruiz-Fernández and Oliva, 2016). Likewise succession of freeze-thaw cycles triggers rock disintegration

facilitating the chemical weathering of the crushed rocks and sediments. Another main factor of soil formation is the biological activity, both by fauna and flora effects. Among the best developed soils in maritime Antarctica are those derived from bird colonies, the Ornithogenic soils have large amounts of nutrients (e.g. [Tatur and Myrcha, 1984](#); [Moura et al., 2012](#); [Pereira, et al., 2013](#)) that further influence soil processes involving the mobilization of chemical elements ([Quayle et al., 2002](#); [Otero et al., 2013](#)). In Cryosols of King George Island [Simas et al. \(2006\)](#) found that non-crystalline phases reach as much as 75% of the clay fraction for some ornithogenic soils and crystalline Al and Fe phosphates occur in the clay at sites directly affected by penguin activity.

Underground water circulation in ice-free areas of maritime Antarctica is connected with active layer depth, also having an effect on soil processes ([Moreno et al., 2012](#)). Furthermore, changes in the duration of the growing season ([Hartley et al., 2010](#); [Bockheim et al., 2013](#)) are promoting the growth of mosses, lichens and Antarctic grasses and the rise of surface covered by plants is also contributing to increased nutrient cycling in the soils ([Otero et al., 2013](#)). The effect of vegetation on the temperature and the relationship between vegetation and active layer thickness has also been pointed out ([Cannone et al., 2006](#)).

The first observations on periglacial processes and soils in Elephant Island were during 1914-1917 Shackleton's expedition, which made initial observations on frost debris covering cliffs ([Wordie, 1922](#)). [Burley \(1972\)](#) pointed out the occurrence of active periglacial processes, such as frost heaving, and landforms such as patterned ground and gelifluction lobes and the existence of permafrost, identifying an active layer between 75 and 159 cm depth. Later works in the western coast ([López-Martínez](#)

et al., 2006, 2012) have identified the geomorphological features and mapped eight different periglacial landforms in the Stinker Point area related to marine platforms (flat floored valleys, laminated cracking on rock, patterned ground, gelifluction sheets and lobes and vertical stone fields), till deposits (patterned ground, gelifluction lobes and vertical stone fields) and slopes (debris talus and cones).

In Elephant Island a minimum age for deglaciation of a specific ice-free area has been dated at around 5.5 ka from a deep moss peat core (Bjorck et al., 1991). However, in other islands of the South Shetlands archipelago, the beginning of deglaciation has been estimated around 9.6 ka in Potter Cove (King George Island), 9.7-6.2 ka in Fildes Peninsula (King George Island) and 8.3-5.9 ka in Byers Peninsula (Livingston Island) (Mausbacher et al., 1989 ; Ingolfsson, 2004; Hall, 2007, 2009). This suggests a possible retreat of the ice in the Elephant Island marine platforms during the early Holocene (9.5-5.5 ka).

Elephant Island (South Shetland Islands) is located between the Drake Passage and the Weddell Sea. As much as 95 % of the total surface area is covered with ice and the ice-free areas are composed of metamorphic rocks showing a contrasting lithology compared to the rest of the South Shetlands. In the island the rock layers are subhorizontal what also affects soil development as the layer orientation parallel to the surface limits pedogenesis. The maritime climate determines the relatively mild conditions in the study region with mean temperatures near the coast ranging from -10° to 1°C and annual precipitation approximately between 500 and 800 mm (Turner and Pendlebury, 2004). Freeze-thaw cycles in the island are generally caused by relatively frequent cyclonic disturbance (Turner et al., 2007) and together with wet environmental conditions and fauna activity are main factors of pedogenesis.

Existing studies on soils of Elephant Island include three profiles in the southern and western coastal areas of the island (O'Brien et al., 1979). Bjorck et al. (1991) completed a paleoclimatic interpretation studying the stratigraphy of a 5,500-year-old moss bank. Following the Walton (1984) soils description on Antarctica, Pereira and Putzke (1994) studied the floristic composition and its relationship with soils. These authors also described the occurrence of ahumic soils, mainly mineral Cryosols, at Stinker Point, as well as Ornithogenic soils related to colonies on low platforms, beaches and moraines, and humic soils, colonised by mosses and Collobantus on slopes and little plains near beaches. Earlier studies by Smith (1972) described the protozoa found in terrestrial environments (moss, soil, clay of moraines and guano) of Elephant Island.

Paraglacial environments are highly sensitive to climate change and are key for identifying its effects upon different earth system compartments thus allowing to examine the influence of time since deglaciation on former glacial landforms and periglacial processes on soil development. Soils record past and present conditions and their characteristics can be a source of information about environmental changes. Such changes can be effectively traced by examining the radionuclides signature and geochemistry features. Despite radionuclides have been proved to have high potential to trace soil redistribution and sediment processes because of its strong association with the fine components of the soil in the last 30 years, it has been only recently when fallout radionuclides have been used to identify characteristics of soil development in paraglacial landscapes (Navas et al., 2014, 2017). To this purpose as a part of a broader study on soils and surface formations in maritime Antarctica, a total of eight soil profiles were collected on two of the main geomorphic elements existing in the island,

raised marine platforms and moraines that were identified during a geomorphological survey carried out in the west and south coasts of Elephant Island largest ice-free areas at Stinker Point and Lindsey Cape. Soil properties, stable elements and activities of fallout (FRN's) and environmental radionuclides (ERN's) analysed in the depth interval samples will be used for assessing soil processes and their relations with geomorphic features which can be of interest for evaluating climate change effects on landforms and soils. Our study aims at characterizing the soils developed on different geomorphic environments and altitudes to investigate the processes involved in their development following the last glacial retreat that started in the area in the Holocene.

MATERIAL AND METHODS

The study area

Elephant Island is located around 61° 10'S - 55°10'W, in the South Shetland Islands, northern Antarctic Peninsula region near the southern boundary of the Scotia Arc (Figure 1). The ice-free areas in the island correspond mainly to cliffs and coastal promontories, high crests, and a series of abrupt scarps and peaks (CGE-UAM-UFRJ, 2005). The underlying materials are composed of phylites, greenschists, blueschists, metabasites, marbles and quartzites metamorphosed in high pressure and low temperature conditions during the Cretaceous (e.g. Trouw et al., 1991, 2000). These rocks show an increase in metamorphism from NE to SW, with zones oriented NW-SE that in the studied western part of the island correspond to serpentine, almandine, green amphibole and biotite metamorphic zones (Trouw et al., 2000). These materials are affected by ductile and brittle deformations, signs of recent uplift (e.g. Galindo-Zaldivar et al., 2006; Mink et al., 2015).

The coast has nearly 120 km length, of which approximately 58% are glaciers reaching the sea and 42% are rocky cliffs and beaches. Glaciers mainly occupy the inlet. In the crest oriented E-W, of about 800 m high, mountain glaciers are aligned flowing to North and South. Among the most extended coastal ice-free areas are Valentine Cape and Belsham Cape in the eastern sector, Lookout Cape, Stinker Point, Mensa Bay, Lindsey Cape, Emma Cove and Yelcho Point in the western coast (CGE-UAM-UFRJ, 2005). The main landforms and landscape elements include platforms, beaches, strandflats, morainic complexes and glaciers (Figure 1). Glacio-isostasy has been proposed as a major responsible of the recent uplift, however neotectonics could also have a participation in recent deformation at Elephant Island (López-Martínez et al., 2006).

In the South Shetland Islands, the occurrence of permafrost has been detected at 50 to 100 cm depths (Bockheim et al., 2013). In Elephant Island, at Stinker Point we observed in January of 2004 an active layer depth of 50 cm on Cerro Mirador (50 m a.s.l.) and 15-30 cm near Goetli Hut (60 m a.s.l.). On the hill located at 90 m a.s.l. the active layer was 30 cm depth and on the lateral moraine (at 90 m a.s.l.) it was 28 cm depth. On beaches and moraines located at 30 m a.s.l. permafrost has not been detected by mechanical sounding. The ice-free areas of Elephant Island support a dynamic active layer of 10-40 cm depth at the beginning of summer reaching 75-150 cm depth at the end of summer, since at least 45 years (Burley, 1972 and our observations).

Soil sampling sites, sample preparation and analysis

Different types of surface deposits are found in the ice-free areas of Elephant Island, namely till forming moraines, deposits on platforms, beach sediments, colluviums and alluviums (Figure 1). Periglacial landforms are developed mainly on moraines and deposits located on platforms, and exceptionally on beaches or on distal parts of slope deposits related to bird colonies and ornithogenic soils.

Sampling was done along two transects (A and B) crossing the two most representative landforms existing in Elephant Island, moraines and marine platforms (Figure 2). A total of seven soil profiles were collected at Stinker Point and another profile was sampled at Lindsey Cape. Four sampling points were on moraines, of which two are located in transect A (A1, A4) and another two in transect B (B1 and B3). Of the four platforms profiles, two were in transect A (A2, A3), one in transect B (B2) and another one in Lindsey Cape (L) at 140 m a.s.l. (Table 2).

The soil profiles were collected until the depth of the parent material was reached or until stone layers or permafrost impede further sampling (15-30 cm). To achieve this plastic containers were hammered on the soil surface and then excavation around to extract an undisturbed soil. Observations on the depth of the active layer around the area of the soil sampling were recorded. Soil profiles were maintained refrigerated in the sealed containers until they were examined in the lab. Each profile was sectioned at 5 cm depth intervals obtaining 3-5 subsamples per site. Profile B3 was a bulk sample as clasts were too large for sectioning.

Samples were air-dried, grinded, homogenized, quartered and sieved at 2 mm to separate and determine the grain size of the coarse and the fine fractions. The soil texture, general soil properties, radionuclides and elemental composition were analysed in the fraction < 2 mm. Sand, silt and clay contents were determined by laser after

eliminating the organic matter with H₂O₂ (10%) heated at 80 °C, disaggregating with sodium hexametaphosphate (40%) by stirring for 2 h and applying ultrasound for few minutes (Navas et al., 2005a). The pH, electrical conductivity (EC), carbonate content, soil organic carbon (SOC), soil nitrogen (SON), extractable phosphorous (P₂O₅) and potassium were analysed in the subsamples (CSIC, 1976). The analyses of the stable 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) were performed by atomic emission spectrometry using an inductively coupled plasma ICP-OES (solid state detector) after total acid digestion with HF (48%) in microwave (Navas and Machín, 2002). Concentrations, obtained after three measurements per element, are expressed in mg/kg.

Gamma emissions of ¹³⁷Cs, ²¹⁰Pb, ²²⁶Ra, ²³⁸U, ²³²Th and ⁴⁰K were measured using a Canberra Xtra high resolution, low background, hyperpure germanium coaxial gamma detector (50% efficiency, 1.9 keV resolution) coupled to an amplifier and multichannel analyser (Navas et al., 2005a, b). Standard certified samples in the same geometry as the measured samples were used for calibration. 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, ¹³⁷Cs activity was determined from the 661.6 keV photopeak; ²¹⁰Pb was measured at 46.5 keV. ²²⁶Ra was determined from the 351.9 keV line of ²¹⁴Pb, a short-lived daughter of ²²⁶Ra, after equilibrium was reached. Unsupported ²¹⁰Pb_{ex} activity was estimated by subtracting ²²⁶Ra from total ²¹⁰Pb and applying a 0.8 correction factor; ²³⁸U was determined from the 63-keV line of ²³⁴Th; ²³²Th was estimated using the 911-keV photopeak of ²²⁸Ac and ⁴⁰K was determined from the 1461 keV photopeak. The radionuclide activities are expressed as Bq kg⁻¹ dry soil.

An ANOVA test was used to assess the statistical significance of the differences in the means of the study parameters at a $p < 0.05$ using the Least Significant Difference (LSD Fisher) test. Principal component analyses were performed to assess the characteristics of soil properties, radionuclides and elemental composition in the soils developed on moraines and platforms.

RESULTS

Landforms and landscape elements

The main landforms and landscape elements we identified in the ice-free areas of Elephant Island are (Figure 1): *Platforms*: little pre-Holocene platforms of marine origin stepped at approximately 50, 70, 90 and 140 m a.s.l. located in the coastal area. The 50 m a.s.l. ice-free platform is the most extensive and it is characterised by the alternation of regolith and substrate outcrops. Glaciers did not occupy these areas during the last glacial advance of the Little Ice Age. In some areas different periglacial features are located on platforms, being patterned ground, stone fields, gelifluction sheets and snow pavements. Debris talus and cones are developed on the slopes of platforms and the paleocliffs linking upper plains and beaches, and sometimes also occupy the higher portion of beaches.

Beaches: little beaches sheltered in small coves under slopes formed by paleocliffs. They are mainly gravel beaches and in their deposits geomorphological features related to frost processes or permafrost have not been detected.

Strandflats: all around the island, in front of beaches and cliffs, an extensive rocky strandflat is developed. It forms a set of flat islands that reduce the wave energy

on cliffs and beaches. Strandflat is free of surface deposits, although in some cases bird colonies generate accumulations of guano and incipient ornithogenic soils.

Morainic complexes: successive crests of lateral and frontal moraines occupy the limits of the present day glaciers. Voluminous moraines of the Little Ice Age form frontal moraines on the paleocliffs and beaches, lateral morainic complex on platforms, and a drumlin field that was developed on the 90 m a.s.l. platform. Extended surfaces of till occupy the high platforms and beaches, especially in the areas of recent deglaciation, such as the SE portion of Stinker Point, where the ice has moved back more than 200 m since it was mapped in 1971 by [Burley \(1972\)](#).

Glaciers: ice domes, apron glaciers and tongue glaciers occupy until the tops, where ice mushrooms sprout. Glaciers dominate the landscape of Elephant Island and a recent retreat during the last 40 years, in some places of several hundreds of meters, allows the presence of recently deglaciated till mantle affected by very active periglacial processes as frost heave and segregation ice.

Moraines and marine platforms occupy the largest ice-free surface in the island, excluding cliffs, crests and scarps. On the first two mentioned landforms processes such as frost, periglacial features and soils with different percentages of mosses and lichens coverage, are related to a permafrost environment with an active layer between 15 and 55 cm depth (Table 1). The most common periglacial features are stone fields, occupying surfaces between 20 and 50 m a.s.l., and patterned ground that spreads between 10 and 140 m a.s.l. ([Serrano et al., 2010](#)). Patterned ground is characterised by well classified sandy textures. Stone fields have predominant relatively fine textures and are generated on small catchments. Gelifluction features exist on all platforms and higher slopes.

286

287 *Soil profile characteristics*

288 On moraines the soil profiles collected are A1, A4, B1 and B3. Profile A1
 289 presents patterned ground and frost heave features. On the top of the moraine the
 290 segregation ice form a frost mound with a 40 cm depth horizontal ice body developed
 291 between the impermeable till and a porous lacustrine deposit composed by stratified
 292 fine layers folded and faulted by the frost action. Partial melt of the ice generates
 293 saturation of the lacustrine and till deposits and slides of several decameters length.
 294 Around the profile site, on morainic slopes, gelifluction lobes disturbing moss and fine
 295 formations are developed indicating intensive periglacial processes linked to permafrost
 296 degradation and active layer. The profile shows a layer of pebbles and small blocks in
 297 planar and upright positions and a sandy layer of 2 cm depth without apparent structure
 298 underlying the non-altered till (Figure 2).

299 Profile A4 is located on the frontal moraine of the Little Ice Age, overlying on
 300 the upper level of Holocene beaches at 30 m a.s.l. The area has a 12° slope and there are
 301 gelifluction and frost heave features around the study profile and the upper layers show
 302 removal processes. The 2 cm upper layer is composed of heterometric pebbles and
 303 blocks in planar layout with mosses and lichens overlying a 6 cm thick layer of gravels
 304 and small pebbles supported by silt and laminated structure. The last layer is non altered
 305 till.

306 Profile B1 is located at 90 m a.s.l. on a drumlin 200 m apart from the glacier
 307 that is made up by partially saturated till. The glacier covered this area in 1971 ([Burley,](#)
 308 [1972](#)). The 2 cm upper layer is composed of pebbles and blocks of clast supported
 309 structure and planar position overlying a 10 cm layer of planar pebbles and blocks

supported by silt matrix. The lower layer is a saturated till of silt-clay texture with the permafrost table at 30 cm depth in December. The weathering of the deposits during the last 40 years occurred by periglacial and nival processes mainly favoured by the high water availability from the glacier and snow melt flowing in the surface or in the active layer, and the low permeability of the permafrost body.

Profile B3 is on the front-lateral moraine of the Little Ice Age overlying the beach, at 30 m a.s.l. The area is an abandoned penguin colony with a 20% surface covered by mosses and algae. The first 30 cm could be disturbed by the penguin selection of coarse material to build nests. The 1-2 cm upper is a clast supported layer formed by homometric pebbles (6-12 cm) in planar position overlying a 3 cm layer of green colour fines. Below there is an 18 cm homometric pebbles layer matrix supported with a wet level in the last 3 cm. The lower layer is a compact till.

On platforms the soil profiles collected are A2, A3, B2 and L. Profile A2 is a weathering profile without external inputs located in the inner area of the middle platform, at 68 m a.s.l. The surface is occupied by stone fields. The structure shows a layer of blocks (10-50 cm of L axis) in planar position and without apparent orientation, with mosses and lichens between clasts covering up to 75%. Underlying the upper layer, a 1-2 cm depth of dry gravel with pebbles and open grained structure with upward compression is developed. A third layer 20 cm thick, is formed by a heterometric sandy deposit without gravels located above the schist substrate. The layer was wet without liquid water flow or saturation. In this location, during the 20 days of summer fieldwork there were 11 days of snowfall and continuous snow melt. The water supply was near 100 mm during December and 8 diurnal-nocturnal freeze-thaw cycles occurred.

Profile A3 is located on the external lower part of the middle platform, at around 60 m a.s.l. and covered by stone fields and snow pavements. The slope is 4°, has good drainage and presents small surface movements, sheet gelifluction and debris lobes. Permafrost is located at 13 cm depth near the study profile. The structure has four alternate layers: a surface level of planar blocks and pebbles oriented to the slope and colonised by lichens (*Usnea*) and moss carpet. The second layer of 10 cm depth formed by gravels with fines has apparent structure. The third layer is composed of gravel and pebbles supported by a sandy matrix 9 cm deep. The fourth layer is a 20 cm compact layer of gravels and pebbles supported with sandy matrix.

Profile B2 is located in the intermediate platform, nearby the LIA lateral moraine, at 60 m a.s.l. A stone field forms the surface. The platform has moss colonization and bird colonies (petrels and penguins). The site is a windy abandoned nesting ground with residues of mattress, eggshell and bird waste on the surface. The upper 1.5 cm layer is composed of pebbles and blocks (48 cm, the longest L axe) in planar position covered by moss and algae (30% cover). A second layer is composed of a silt matrix with sand and clay, including small pebbles and gravel. The third layer is dominated by coarse fraction of pebbles and blocks (14 cm, the longest L axe) in planar position with massive structure supported by silt matrix. This formation reaches the permafrost table at 29 cm depth.

Profile L corresponds to the general surface coverage of the marine erosive platform at 140 m a.s.l., which in this point is 20 cm depth, having a surface with abundant pebbles and blocks. The sampling point is at about 10 m from the scarp of this well-developed raised marine platform.

357 *General soil properties*

358 The soils of Elephant Island have abundant stones (Table 3), mostly composed
 359 of boulders and cobbles of angular and planar shapes, pebbles and gravels. The coarse
 360 fraction (> 2 mm) ranges from 17 to 71 % and in average amounts around 40%. The
 361 weathering deposits on platform profiles A3 and till profile B3 had the largest coarse
 362 fraction contents, of what boulders take as much as 49 %. The range of the fine fraction
 363 (< 2 mm) varied between 29 and 83 % and in average takes up to around 60 % of the
 364 total content with the largest fine percentages found in the topsoil of platform profiles
 365 A2 and B2. The soils on platforms show the largest variations with significantly higher
 366 mean content of gravels than soils on moraines while boulders are almost negligible in
 367 the Lindsey Cape profile. Decreasing and increasing contents of the coarse fraction with
 368 depth occur in both landforms (Figure 3). Silt is the most abundant fine fraction (range:
 369 23 – 82 %) and its content is significantly higher in soils on moraines than on platforms
 370 as well as clay (range: 3 – 16 %) but the opposite is found for the sand fraction (range: 2
 371 – 72 %), which is significantly higher in soils on platforms. Textures are loamy silt and
 372 loamy sand. Clay and silt contents increase with depth in the moraine profiles A4 and
 373 B1 but soils on platforms do not exhibit any clear trend.

374 The soil pH varied largely from 3.9 to 8.6. The soils on platforms were acidic
 375 but they were alkaline on moraines (Table 3) in coincidence with significantly higher
 376 carbonate contents than on platforms despite their low values (range: bdl – 1 %). In
 377 general, pH and carbonates had quite similar depth distribution patterns. The pH tended
 378 to decrease with depth in soils on platforms (apart from L profile) but the opposite was
 379 found in A1 and B1 till profiles that increased with depth in parallel to the carbonate

content (Figure 3). The studied soils had low salinity values (range: 0.034 – 1.105 dS m⁻¹) and larger variations were observed in soils on platforms.

The SOC varied from 0.16 up to 1.6 % (Figure 3) and contents were significantly higher in the soils on platforms reaching the highest value at the upper layers of A2. Similarly, SON ranged from 0.02 to 0.33 % being significantly higher in soils on platforms with the highest values in profiles A2 and B2 as well as in the till profile B3, an abandoned penguin nesting site. The largest variations in contents of SOC and SON with depth were also in soils on platforms. The values of mean SOC/SON ratio were higher and less variable in soils on moraines but were not significantly different from mean ratio in soils on platforms.

The extractable phosphorous (P₂O₅) was highly variable, from below detection levels up to as much as 3780 mg kg⁻¹ in B3. Although the most frequent range was between 100 and 200 mg kg⁻¹, very low values were detected in the till profile B1 (covered by ice until 1971) and the L profile located at 140 m a.s.l. The extractable K also had a wide range of variation from 34 up to 373 mg kg⁻¹. The mean values of K were significantly higher in soils on weathering deposits on platforms than on moraines. The depth distribution of extractable phosphorous and potassium was very similar in soils on moraines but this was not the case on platforms where apart from profile L, the extractable K showed large variations in comparison with the mostly homogeneous vertical distribution of extractable P (Figure 3).

Geochemical composition: stable elements and radionuclides

The most abundant stable elements in the soils of Elephant Island were Al and Fe, ranging between 43700 to 53900 mg kg⁻¹ and between 32300 to 51200 mg kg⁻¹,

respectively. The moraine profile B3 presented the lowest contents of both Fe and Al. Among the major elements Ca and Na ranged between 16200 and 35700 mg kg⁻¹ and between 16400 and 30000 mg kg⁻¹, respectively. Contents of K, Mg and Mn varied from 4350 to 10800 mg kg⁻¹ for K, from 2975 to 6600 mg kg⁻¹ for Mg and from 700 to 2200 mg kg⁻¹ for Mn. Contents of minor elements Pb, Ba and Sr ranged from 180 to 250 mg kg⁻¹ for Pb, from 140 to 250 mg kg⁻¹ for Sr and from 84 to 500 mg kg⁻¹ for Ba, with the exception of very high contents found in profile L where Ba reached up to 2000 mg kg⁻¹. As trace elements the most abundant were Zn, Cr and Cu ranging from 58 to 222 mg kg⁻¹ for Zn, from 6 to 100 mg kg⁻¹ for Cr and from 4 to 62 mg kg⁻¹ for Cu. Contents of Li, Co and Ni were low, ranging from 30 to 50 mg kg⁻¹ for Li, from 2 to 31 mg kg⁻¹ for Co and from 2 to 27 mg kg⁻¹ for Ni. The content of Cd was the lowest varying between 0.75 to 4.46 mg kg⁻¹ while it was not detected in the L profile at Lindsey Cape.

As presented in Table 4, the geochemical composition of the studied soils was in general quite similar and only significant differences were found in the mean contents of Na which was higher in soils on weathering deposits than on till, whereas the opposite was found for the trace metals Cu, Co and Ni that were significantly lower in comparison with their means in soils on moraines.

The vertical distribution of the major elements Al, Fe, Ca, Na and Mn was quite homogeneous with the largest variations observed in the weathered deposits profiles A2, A3 and L on platforms (Figure 4). Potassium and to less extent Mg were quite variable in all soil profiles. Zn, Ba and Cu showed the greatest variations in soils of platforms but were more uniform in the profiles of soils on moraines. Chromium and Li,

Sr and Pb as well as Co and Ni had similar depth distribution patterns. The trace element Cd was the most homogeneous with depth in all profiles.

The fallout radionuclides ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ had distinctive features (Figure 5). The artificial ^{137}Cs was found in the upper layers of two platform profiles, A2 and A3, and only in one soil on moraines, the bulk B3. The $^{210}\text{Pb}_{\text{ex}}$ was found in all profiles to depths of around 15 cm but it was even found in the 20-25 cm interval of platform soils. The ^{137}Cs mass activity ranged between b.d.l. and 11.1 Bq kg^{-1} but that of $^{210}\text{Pb}_{\text{ex}}$ was higher ranging between b.d.l. and 25.1 Bq kg^{-1} . The $^{210}\text{Pb}_{\text{ex}}$ profiles showed exponential decay in two of the platform profiles but the decreasing patterns in mass activities were not seen in soils on moraines. The mean activities of $^{210}\text{Pb}_{\text{ex}}$ were higher and had the largest variations in soils on platforms although differences were not significant from mean activities on moraines (Table 4).

The mass activities of the radionuclides of the uranium/thorium decay chain were low with ranges from 11.6 to 29.4 Bq kg^{-1} for ^{226}Ra , from 12.8 to 30.9 Bq kg^{-1} for ^{232}Th and from 12.0 to 33.5 Bq kg^{-1} for ^{238}U . The mass activities of ^{40}K ranged from 226 to 904 Bq kg^{-1} with highest contents in the platform profile L (mean: 850 Bq kg^{-1}), between 2 and 4 times the contents in the rest of the profiles. Mean contents of the environmental radionuclides were slightly higher and more variable in soils on platforms but compared with that on moraines differences were not significant (Table 4). Vertical distribution of the environmental radionuclides presented variations with depth (Figure 5) especially ^{238}U and ^{232}Th . The depth pattern of ^{40}K was not clear showing both increasing and decreasing patterns with depth.

The soil properties, radionuclides and stable elements contents were used for the Principal Component Analysis shown in Figure 6. The 3D scatter plot of the three

principal components for all the study profiles were clearly distinctive for moraine and platform soils. Considering the studied landforms separately, components PC1 and PC2 – with eigenvalues higher than 1– accounted for 97% of the variation in moraine soil profiles and 87% of the variation in soils on platforms. In the case of moraine soils, the first principal component showed positive correlation with EC, sand, soil nutrients, SOC and SON, the fallout radionuclides (^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$) and the environmental radionuclides ^{226}Ra and ^{232}Th and with Na, Zn, Sr, Mn and Cu. Conversely, the first principal component showed negative correlation with the fine fractions silt and clay, pH and carbonates, ^{40}K and ^{238}U and the rest of stable elements. In soils on platforms the first principal component presented negative correlations with the nutrients, apart from SOC, clays, the fallout radionuclides (^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$) and Na, Mn, Co, Ni, Cu, Cr, Cd and Ca. Conversely it showed a positive correlation with pH, the environmental radionuclides and the rest of the stable elements.

DISCUSSION

General soil properties

In Elephant Island during the snow melt period, with a thin active layer, soils remain saturated undergoing frost heave, freezing cycles, segregation ice or mass movements. All these processes generate landforms such as stone fields, patterned ground or lobes on slopes. Permafrost is found on the platforms above 50 m a.s.l., and the active layer reaches between 30 cm and 150 cm depth as it was measured on moraines between November and February. Phenomena associated with frozen ground include patterned ground, frost mounds, gelifluction lobes and protalus lobes. The most widespread forms are clasts mantles, characterized by pebbles and boulders in planar

position on thin accumulations of fine material (silt and sand) which are placed in platforms and in flat zones of till. Therefore, periglacial and cryogenic processes play a key role in the abundance of coarse material in the study soils. On the till accumulations periglacial landforms related to segregation ice, frost heave and active layer processes have developed. These are mainly gelifluction lobes, frost mounds and patterned ground, with till weathering only in the upper centimetres of the deposit (20-40 cm). On platforms, soils spread on their surfaces are the best places for occurrence of periglacial processes linked also to the active layer and the presence of snow. Among most common periglacial features, stone fields and snow pavements also determine the abundance of coarse material. There are significant differences in gravels content in comparison with predominant boulders in the soils on moraines suggesting differences in the periglacial processes between landforms. As [Serrano et al. \(2010\)](#) found in a previous study in the island, patterned ground is mainly generated on relatively deep surface deposits of till and poorly drained areas with constant feed snow melt forming water saturated areas in summer. However, stone fields are generated in well drained or dry areas, mainly on poorly sorted clast mantles but also to a lesser extent on till and colluviums. In weathering deposits on platform profiles the water availability and freeze-thaw cycles explain the organization of the upper structure, with fines washing, push up of gravels and planar positions of pebbles and blocks.

The freeze-thaw weathering is widely recognized as a main cause of rock disintegration ([Hall, 1993](#); [Serrano et al., 1996](#)) as evidenced by the higher abundance of the fine fraction in the study soils. The succession of cycles of wetting and drying may be related to the abundance of fines but the higher sand content and gravels in the soils of weathering deposits on platforms could be also related to the effect of the sea

action by comparison with till. Furthermore, the effect of the altitude controlling the number of cycles during the summer season has also to be considered in the grain size features. Previous studies in King George Island (Chen et al., 2000; Michel et al., 2014) and Livingston Island (Navas et al., 2006, 2008, 2017) suggest that poorly developed soils appear on surfaces with patterned ground and freeze-thaw cycles.

The marked difference between the acidic soils on platforms and the alkaline soils on moraines correspond to the more recent exposure of the latter that preserve most the characteristics of the parent material as the close link with carbonates in the depth profiles of soils on moraines also suggests. These patterns coincide with the geographical distribution of alkaline pH values linked to that of parent material found in the proximity to glaciers and tending to acidification towards the coast, where fauna activity increases producing strong acids by the mineralization of guano (Tatur and Barczuk, 1985) and soil processes had been acting longer (Bölter et al., 1997; Bölter, 2011; Wilhelm et al., 2016; Navas et al., 2017).

The general low salinity of the soils despite of being close to the sea is likely due to dilution of marine aerosols by rain and abundant melting waters that would infiltrate in the soil profile leaching soluble salts as found in soils of King George Island (Lee et al., 2004) and of Livingston Island (Navas et al., 2006, 2008, 2017). Therefore, variations of the depth of active layer affecting water infiltration is related to soil salinity by diluting salts with higher water circulation at deeper permafrost. The largest variations in the platforms and the highest values found at the middle layers of A3 are likely due to the effect of ornithogenic activity because of its coincidence with high values of SON and extractable P.

The greater content of SOC in the soils on platforms is linked to the larger abundance of vegetation cover of mosses. As found in other Antarctica enclaves (Bockheim, 1997; Beyer et al., 1998) as well as in Livingston Island (Navas et al., 2006, 2008, 2017) high contents of SOC are found in moss-dominated soils (Wilhelm et al., 2016). The vegetation cover has been found to be a key factor on soil development in the maritime Antarctica region (Otero et al., 2013). Similarly, higher SON contents in soils on platforms by comparing to moraine soils correspond to greater and longer fauna activity in the former, which is confirmed by the higher SOC/SON ratios found in moraine soils. Higher surface stability in platforms could also be a factor influencing the mentioned fauna preference. To this respect seabirds have a key role together with atmospheric agents in disseminating seeds (Quesada et al., 2009; Otero et al., 2013; Ruiz-Fernández et al., 2017). Seabirds are also responsible for the high nutrient contents found in coastal soils (Beyer et al., 2000) such as high SOC content in places on intermediate platforms of Elephant Island that are abandoned penguin colonies (Simas et al., 2007).

The extractable P and K contents are related to fauna activity in profiles A3 and B3, which is an abandoned nesting site. In non-ornithogenic profiles as B1 (covered by ice until 1971) and L located at 140 m a.s.l., the origin of P is likely related to the dissolution of apatite from parent material. Moreover, the parallelism between the depth distribution of extractable P and K in soils on moraines could be related to the mineralogical association of P-rich minerals with K-feldspars as found in soils of Livingston Island (Navas et al., 2008). The extractable P contents in our study soils are moderate in comparison with the high P contents in ornithogenic soils of Cierva Point (Wilhelm et al., 2016) and in one of the 3 soil profiles previously characterized by

O'Brien et al. (1979) in Elephant Island. We found enrichment of P in the profiles where fauna activity was clearly identified as documented in other ornithogenic soils of maritime Antarctica (Blume et al., 1997; Simas et al., 2008; Souza et al., 2014). Moura et al. (2012) refer to the effect of seabirds on the alteration of clay mineralogy and the subsequent formation of poorly crystalline P-rich phases. Previous studies by Wilson and Bain (1976, 1986) identified an ammonium-rich leucophosphate as well as a new phosphate mineral occurring in soils of Elephant Island in areas of penguin nesting. The importance of phosphatization in the characteristics of ornithogenic soils (Ugolini, 1972; Tatur and Barczuk, 1985) including P and N enrichment and enhancement of vegetation growth as observed in our study soils and consequent increase of soil organic C content, make Ornithogenic soils one of the most important C sinks in terrestrial ecosystems of Antarctica (Simas et al., 2007).

Geochemical composition for inferring soil and geomorphic processes

The mineralogical composition of the metamorphic rocks underlying the ice-free surface of Elephant Island drives the geochemical composition of the soils found in the study profiles. In an earlier study of 3 soil profiles in Elephant Island, mineral weathering was found to be very limited as indicated by the minerals in the sand and clay fractions (O'Brien et al., 1979). In our soils the mean contents of the major elements Al, Fe, Ca and K are likely related to silicates mineralogy (feldspars, sheet silicates) as well as most of the rest of stable elements and does not differ in soils on till and on weathering deposits suggesting a general common origin. This is further supported by the general parallelism in the depth distribution of these four major elements. The greater content of Na in soils on platforms may also be related with the

mineral composition of bedrocks that would suggest a relatively higher abundance of alkali feldspars (Kabata-Pendias and Pendias, 2001). However, greater contents of Cu, Ni and Co in the soils on till are likely linked to higher abundance of argillaceous minerals bearing these elements in till than in weathering deposits on platforms. In contrast to this the L profile of Lindsay Cape with the lowest contents in these three trace elements would suggest less abundance of argillaceous minerals in coincidence with the lower content of the clay fraction in this profile. In turn, the absence of Cd and the highest content of Ba in L profile could be related to higher abundance of alkali feldspars (Kabata-Pendias and Pendias, 2001) indicating that this enclave has a distinctive mineralogy. Similarities in the elemental abundance are shared with other enclaves in South Shetland Islands (Byers and Hurd Peninsulas and Elephant Point in Livingston Island (Navas et al., 2006, 2008, 2017) however, in Elephant Island Al, likely derived from silicates, is the most abundant element.

The effect of seabird-derived enrichment in nitric acids seems to be responsible for the largest vertical variations observed in the contents of most stable elements and the environmental radionuclides in the soil profiles of the platforms in comparison with those on moraines. As found in other temperate and cold regions environmental radionuclides are affected by soil processes influencing their vertical variations (Navas et al., 2002 a, b; 2014). Enhanced chemical weathering has been reported at sites around nesting penguins (Blume et al., 2002; Simas et al., 2006). Furthermore, in the acid soils of the platforms covered by mosses and algae the input of protons derived from plants and microorganisms and organic acids will also favour the mobilization of elements down the soil profile. This agrees with accelerated leaching associated to biological activity reported by Allen (2005) and Otero et al. (2013) in coastal environments of

maritime Antarctica that would facilitate the bioavailability of macro and micronutrients (e.g. de Mora et al., 1994; Munroe et al., 2007).

The presence of ^{137}Cs in the upper layers (0-5, 0-10 cm) of two platform profiles (A2 and A3) where the vegetation cover of mosses is abundant and contents of SOC are the highest confirm their close link related to the preferential fixation of the radionuclide by the organic matter (Gaspar and Navas, 2013; Gaspar et al., 2013) and its associated redistribution with soil by physical processes (Soto and Navas, 2004, Navas et al., 2012). The depth penetration of ^{137}Cs is comparable to that found in Livingston Island (Navas et al., 2005a, 2017). The absence of ^{137}Cs in the other two platform profiles is likely due to the scarcer vegetation but also to fauna disturbance in the case of B2, an old abandoned nesting area. Absence of ^{137}Cs in the L profile could be due to both the lower SOC content especially depleted at the topsoil and the altitude (140 m a.s.l.) meaning longer duration of snow cover at this site that could restrict the fixation of the radionuclide. In the soils on moraines the absence of ^{137}Cs , apart from B3, is related to the low SOC content, despite the higher amounts of clay fractions. In the case of B1 that was covered by ice until 1971 is because this site was only exposed after the ^{137}Cs peak fallout. However, the presence of ^{137}Cs in B3 is likely due to the higher amounts of SOC in this site, related to the presence of mosses and ornithogenic activity in comparison with the other moraine sites. Therefore, in contrast with moraine sediments in Elephant Point (Livingston Island) that had neither SOC nor ^{137}Cs (Navas et al., 2017), the longer exposure of the study soils on moraines of LIA age under the more favourable climate conditions of Elephant Island with higher rainfall and warmer temperatures have facilitated the expansion of the vegetation cover. In this way incipient soils containing SOC though low contents along with the fauna activity in B3

have provided the soil conditions to fix the radionuclide. The differential depth distribution of $^{210}\text{Pb}_{\text{ex}}$ and its deeper penetration in the soils on weathering deposits on platforms is also due to the more developed soil characteristics in these longer deglaciated landforms.

The different association of the studied soil properties, radionuclides and stable elements in soils on moraines and platforms are indicative of differential stages of soil development and of processes operating in both landforms in this paraglacial environment. In weathering deposits on platforms soil nutrients (SOC, SON, extractable P and K) and FRNs are associated with the fine fractions (clay and silt) (Figure 6). On the contrary, on moraine sites an association of fine fractions, clay and silt with ^{40}K and ^{238}U and Fe and Al among the major elements are found and soil nutrients appear along with sand, FRNs and the rest of ERNs as well as with Ca and Na suggesting a more incipient status of soil development on moraines. FRNs are fixed on the soil fine components when soils have a certain degree of soil development as to contain a certain amount of organic carbon and clays. As recorded in very recently deglaciated moraine sediments of Elephant Point (Livingston Island) where soils had not developed yet, SOC and ^{137}Cs were not present (Navas et al., 2017).

Depending on the duration of exposure since glacial retreat we found more developed soils on the platforms that were deglaciated around Early Holocene compared to that on moraines of LIA. On the slopes and ridges of the outer arches surfaces may have remained free of ice between 500 and 150 years ago and on the highest morainic complexes and till cover for less than 40 years. The ease of water infiltration promoting deeper penetration of $^{210}\text{Pb}_{\text{ex}}$ in the soils on platforms occurs in areas of thicker active layer where permafrost is deeper fostering mineral weathering.

That along with ornithogenic activity in lower surfaces closer to the coast would activate leaching processes that are more relevant in the soils developed on weathering deposits on platforms in comparison with soils on moraines.

Differences among the geomorphic features found at the different altitudes suggest an important control of the physiographic and hydrological conditions on physical weathering. The intense physical weathering through freeze-thaw cycles produces a strong reworking of the materials hampering the formation of soil horizons (O'Brien et al., 1979). Freeze-thaw cycles within the active layer, wetting-drying and cryoturbation are main processes taking place that contribute to rock disintegration providing the basis for soil formation. The most intense periglacial processes are developed on the platforms and moraines above 50 m a.s.l., disturbing the weathering deposits, till and colluvium. The existence of permafrost and an annually changing active layer support the water saturation and flow by active layer to produce intense periglacial processes related to cryoturbation.

CONCLUSIONS

The soils of the study area have developed after the last glacial advances of Holocene age (9.5-5.5 ka.) on the weathering deposits of the platforms. The longest exposure of materials on platforms is conducive to the development of Cryosols, and ornithogenic activity is a main agent promoting leaching and mobilization of elements and nutrients, while on moraines, leaching processes are much more limited. Ornithogenic activity also contributes to the soil formation on LIA moraine complexes. On moraines the soils are more recent and have developed since 500 yr BP in the case of the outer arches and after the LIA in the case of the highest moraines (less than 40 yr

BP). Signs of surface periglacial alteration, with planar organization of surface clasts is related to the original position of parent material and frost heave processes.

The distribution patterns of main soil properties and geochemistry are related to the parent material and geomorphic processes. Geochemical characteristics indicate that the main process involved in soil development is the mechanical disintegration of bedrocks. Cryogenic processes play a key role in soil development while chemical weathering processes are less extended and controlled by the depth of permafrost and the water circulation, which is limited to summer. Differences among soil characteristics and properties at the different altitudes indicate an important control of the physiographic conditions over the main soil forming agents and different adjustment to the transitional conditions during paraglacial landscape response.

In comparison with other islands of maritime Antarctica both lithology and subhorizontal bedding of rock outcrops are the reason for differences in weathering intensity found in Elephant Island. Over the more resistant metamorphic parent material existing in the island along with the planar position of soil clasts both physical and chemical weathering are restricted resulting in poorly developed soils.

As found in other enclaves of the South Shetland Islands the soils of Elephant Island are also scarcely developed, pedogenesis and geochemical processes in general are of limited extent and chemical weathering is still incipient in comparison with cryoturbation processes favoured by warmer temperatures and high water availability. Comparatively in the study soils cryoturbation processes are more energetic providing the soils their most characteristic traits. This is especially the case for the most newly formed soils on till that still maintain the characteristics of the parent material (reflected in pH value) and are relatively less colonized by vegetation. Our results evidence that

SOC content and FRNs are key properties to assess the degree of soil development on which vegetation cover and ornithogenic activity are crucial.

ACKNOWLEDGEMENTS

This work is supported by the Projects CTM2014-57119-R and CGL2014-52986-R of the Spanish R&D National Plan. The fieldwork was possible thanks to the logistic support of the Brazilian Antarctic Programme. The authors acknowledge the comments of the referees and the editor, which have contributed to improve the manuscript.

REFERENCES

- Allen CE. 2005. Physical and chemical characteristics of soils forming on boulder tops, Kärkevagge, Sweden. *Soil Science Society of America Journal* **69**: 148–158. DOI: 10.2136/sssaj2005.0148
- Balks MR, López-Martínez J, Goryachkin S, Mergelov N, Schaefer C, Simas F, Almond P, Claridge GCG, McLeod M, Scarrow J. 2013. Windows on Antarctic soil landscape relationships: comparison across selected regions of Antarctica. In Hambrey MJ et al. (eds.). *Antarctic Palaeoenvironments and Earth-Surface Processes*. London, Special Publications of the Geological Society of London **381**: 397-410. DOI: 10.1144/SP381.9
- Beyer L, Pingpank K, Bölter M, Seppelt RD. 1998. Small-distance variation of carbon and nitrogen storage in mineral Antarctic cryosols near Casey Station (Wilkes

- Land). *Journal of Plant Nutrition and Soil Science* **161**: 211-220. DOI:
10.1002/jpln.1998.3581610306
- Beyer L, Pingpank K, Wriedt G, Bölter M. 2000. Soil formation in coastal continental
Antarctica (Wilkes Land). *Geoderma* **95**: 283–304. DOI: 10.1016/S0016-
7061(99)00095-6
- Björck S, Malmer N, Hjort C, Sandgren P, Ingólfsson Ó, Wallen B, Smith RIL,
Liedberg-Jönsson B. 1991. Stratigraphic and palaeoclimatic studies of a 5,500 years
old moss bank on Elephant Island, Antarctica. *Arctic and Alpine Research* **23**: 361-
374. DOI: 10.2307/1551679
- Blume HP, Beyer L, Bölter M, Erlenheuser H, Kalk E, Kneesch S, Pfisterer U,
Schneider D. 1997. Pedogenic zonation in soils of southern circumpolar region.
Advances in GeoEcology **30**: 69–90
- Blume HP, Beyer L, Kalk E, Kuhn D. 2002. Weathering and soil formation. In: Beyer
L, Bölter M. (eds), *Geoecology of Antarctic Ice-Free Coastal Landscapes*. Berlin.
Ecological Studies 154, Springer, pp: 115-138
- Bockheim JG. 1997. Properties and classification of cold desert soils from Antarctica.
Soil Science Society of America Journal **61**(1): 224-231. DOI:
10.2136/ssaj1997.03615995006100010031x
- Bockheim JG. 2015. *The Soils of Antarctica*. World Soils Book Series, Springer,
Dordrecht. DOI: 10.1007/978-3-319-05497-1_1
- Bockheim J, Vieira G, Ramos M, López-Martínez J, Serrano E, Guglielmin M, Wilhelm
K, Nieuwendam A. 2013. Climate warming and permafrost dynamics in the
Antarctic Peninsula region. *Global and Planetary Change* **100**: 215–223. DOI:
10.1016/j.gloplacha.2012.10.018

- 736 Bølter M. 2011. Soil development and soil biology on King George Island, Maritime
737 Antarctic. *Polish Polar Research* **32**(2): 105–116. DOI: 10.2478/v10183-011-
738 0002-z
- 739 Bølter M, Blume HP, Schneider D, Beyer L. 1997. Soil properties and distribution of
740 invertebrates and bacteria from King George Island (Arctowski Station), maritime
741 Antarctic. *Polar Biology* **18**: 295–304. DOI: 10.1007/s003000050191
- 742 Burley M. 1972. Joint Services expedition to Elephant Island. *Geographical Journal*
743 **138**: 298-308. DOI: 10.2307/1795437
- 744 Campbell IB, Claridge CGC. 1987. *Antarctica: soils weathering processes and*
745 *environment*. Developments in Soil Sciences, vol. 6. Amsterdam. Elsevier Science
746 Publishers B.V., 368 pp. DOI: 10.1002/esp.3290140811
- 747 Cannone N, Ellis-Evans JC, Strachan R, Guglielmin M. 2006. Interactions between
748 climate, vegetation and the active layer in soils at two Maritime Antarctic sites.
749 *Antarctic Science* **18**(3): 323-333. <https://doi.org/10.1017/S095410200600037X>
- 750 CGE-UAM-UFRJ. 2005. *Isla Elefante/Elephant Island, Antártida*. Mapa E. 1:50 000.
751 Serie Cartografía Antártica. Madrid, Centro Geográfico del Ejército
- 752 Chen J, Zitong G, Blume HP. 2000. Soils of Fildes Peninsula, King George Island, the
753 maritime Antarctic: Part 1, Formation processes and pedogenetic particularities.
754 *Chinese Journal of Polar Science* **11**(1): 25-38
- 755 CSIC 1976. Comisión de métodos analíticos. *Anales de Edafología y Agrobiología* **35**:
756 813-814
- 757 De Mora SJ, Whitehead RF, Gregory M. 1994. The chemical composition of glacial
758 meltwater ponds and streams on the McMurdo Ice Shelf, Antarctica. *Antarctic*
759 *Science* **6**: 17–27. DOI: 10.1017/S0954102094000039

- Galindo-Zaldívar J, Maestro A, López-Martínez J, Sanz de Galdeano C. 2006. Elephant Island recent tectonics in the framework of the Scotia-Antarctic-South Shetland Block triple junction (NE Antarctic Peninsula). In Fütterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F. (eds). *Antarctic Contributions to Global Earth Science*, 5.8, 271-276. Berlin-Heidelberg-New York: Springer. DOI: 10.1007/3-540-32934-x_33
- Gaspar L, Navas A. 2013. Vertical and lateral distributions of ^{137}Cs in cultivated and uncultivated soils on Mediterranean hillslopes. *Geoderma* **207-208**: 131–143. DOI: 10.1016/j.geoderma.2013.04.043
- Gaspar L, Navas A, Walling DE, Machín J, Gómez Arozamena J. 2013. Using ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ to assess soil redistribution on slopes at different temporal scales. *Catena* **102**: 46–54. DOI: 10.1016/j.catena.2011.01.004
- Hall K. 1993. Rock moisture data from Livingston Island (Maritime Antarctic) and implications for weathering studies. *Permafrost and Periglacial Processes* **4**: 245–253. DOI: 10.1002/ppp.3430040306
- Hall BL. 2007. Late-Holocene advance of the Collins Ice Cap, King George Island, South Shetland Islands. *Holocene* **17-18**: 1253–1258. DOI: <https://doi.org/10.1177/0959683607085132>
- Hall BL. 2009. Holocene glacial history of Antarctica and sub-Antarctic Islands. *Quaternary Science Reviews* **28**: 2213-2230. DOI: <https://doi.org/10.1016/j.quascirev.2009.06.011>
- Hartley IP, Hopkins DW, Sommerkorn M, Wookey PA. 2010. The response of organic matter mineralisation to nutrients and substrate additions in sub-arctic soils. *Soil Biology and Biochemistry* **42**: 92–100. DOI: 10.1016/j.soilbio.2009.10.004

- 784 Ingólfsson Ó. 2004. Quaternary glacial and climate history of Antarctica. In Ehlers J,
785 Gibbard PL. (eds), *Quaternary Glaciations-Extent and Chronology*, Part III.
786 Elsevier, pp. 3-43
- 787 Kabata-Pendias A, Pendias H. 2001. Trace element in soils and plants. Boca Raton,
788 CRC Press.
- 789 Lee Y, Lim HS, Yoon YI. 2004. Geochemistry of soils of King George Island, South
790 Shetland Islands, West Antarctica: Implications for pedogenesis in cold polar
791 regions. *Geochimica et Cosmochimica Acta* **68**(21): 4319–4333. DOI:
792 10.1016/j.gca.2004.01.020
- 793 López-Martínez J, Schmid T, Serrano E, Mink S, Nieto A, Guillaso S. 2016.
794 Geomorphology and surface landforms distribution in selected ice-free areas within
795 the South Shetland Islands, northern Antarctic Peninsula region. *Cuadernos de*
796 *Investigación Geográfica* **42**(2): 435-455. DOI: 10.18172/cig.2965
- 797 López-Martínez J, Serrano E, Schmid T, Mink S, Linés C. 2012. Periglacial processes
798 and landforms in the South Shetland Islands (Northern Antarctic Peninsula region).
799 *Geomorphology* **155-156**: 62-79 - DOI: 10.1016/j.geomorph.2011.12.018
- 800 López-Martínez J, Trouw RAJ, Galindo-Zaldívar J, Maestro A, Simoes LSA, Medeiros
801 FF, Trouw CC. 2006. Tectonics and geomorphology of Elephant Island, South
802 Shetland Islands. In Fütterer DK, Damaske D, Kleinschmidt G, Miller H,
803 Tessensohn F. (eds), Berlin-Heidelberg-New York: Springer *Antarctic*
804 *Contributions to Global Earth Science* 5.9. DOI: 10.1007/3-540-32934-x_34
- 805 Mausbacher R, Muller J, Munnich M, Schmidt R. 1989. Evolution of postglacial
806 sedimentation in Antarctic lakes (King George Island). *Zeitschrift für*
807 *Geomorphologie* **33**: 219–234.

- 808 Michel RF, Schaefer CEGR, López-Martínez J, Simas FNB, Haus NW, Serrano E,
809 Bockheim JG. 2014. Soils and landforms from Fildes Peninsula and Ardley Island,
810 Maritime Antarctica. *Geomorphology* **225**: 76-86.
811 DOI:10.1016/j.geomorph.2014.03.041
- 812 Mink S, Maestro A, López-Martínez J, Schmid T, Galindo-Zaldívar J, Trouw RAJ.
813 2015. Morphostructural analysis and Cenozoic evolution of Elephant Island,
814 Southern Scotia Arc, Antarctica. *International Journal of Earth Sciences* **104**: 833-
815 851. DOI: 10.1016/j.geomorph.2014.03.028
- 816 Moreno L, Silva-Busso A, López-Martínez J, Durán JJ, Martínez-Navarrete C, Cuchí
817 JA, Ermolin E. 2012. Hydrogeological characteristics at Cape Lamb, Vega Island,
818 Antarctic Peninsula. *Antarctic Science* **24**(6): 591-607. DOI:
819 10.1017/S0954102012000478
- 820 Moura PA, Francelino MR, Schaefer CEGR, Simas FNB, Mendonça BAF. 2012.
821 Distribution and characterization of soils and landform relationships in Byers
822 Peninsula, Livingston Island, maritime Antarctica. *Geomorphology* **155-156**: 45–
823 54. <https://doi.org/10.1016/j.geomorph.2011.12.011>
- 824 Munroe JS, Farrugia G, Ryan PC. 2007. Parent material and chemical weathering in
825 alpine soils on Mt. Mansfield, Vermont, USA. *Catena* **70**: 39–48. DOI:
826 10.1016/j.catena.2006.07.003
- 827 Navas A, Machín J. 2002. Spatial distribution of heavy metals and arsenic in soils of
828 Aragón (northeast Spain): controlling factors and environmental implications.
829 *Applied Geochemistry* **17**: 961–973. DOI: 10.1016/S0883-2927(02)00006-9

- 830 Navas A, Soto J, Machín J. 2002a. ^{238}U , ^{226}Ra , ^{210}Pb , ^{232}Th and ^{40}K activities in soil
831 profiles of the Flysch sector (Central Spanish Pyrenees). *Applied Radiation and*
832 *Isotopes* **57** (4): 579–589. DOI: 10.1016/S0969-8043(02)00131-8
- 833 Navas A, Soto J, Machín J. 2002b. Edaphic and physiographic factors affecting the
834 distribution of natural gamma-emitting radionuclides in the soils of the Arnás
835 catchment in the Central Spanish Pyrenees. *European Journal of Soil Science* **53**:
836 629–638. DOI: 10.1046/j.1365-2389.2002.00488.x
- 837 Navas A, Soto J, López-Martínez J. 2005a. Radionuclides in soils of Byers Peninsula,
838 South Shetland Islands, Western Antarctica. *Applied Radiation and Isotopes* **62**(5):
839 809–816. DOI: 10.1016/j.apradiso.2004.11.007
- 840 Navas A, Machín J, Soto J. 2005b. Assessing soil erosion in a Pyrenean mountain
841 catchment using GIS and fallout ^{137}Cs . *Agriculture, Ecosystems & Environment*
842 **105**: 493–506. DOI: <http://dx.doi.org/10.1016/j.agee.2004.07.005>
- 843 Navas A, López-Martínez J, Casas J, Machín J, Serrano E, Durán JJ, Cuchí JA. 2006.
844 Soil characteristics along a transect on raised marine surfaces on Byers Peninsula,
845 South Shetland Islands. In Fütterer DK, Damaske D, Kleinschmidt G, Miller H,
846 Tessensohn F. (eds), Berlin-Heidelberg-New York: Springer, *Antarctic*
847 *Contributions to Global Earth Science* 8.9, 467-474. DOI: 10.1007/3-540-32934-
848 x_60
- 849 Navas A, López-Martínez J, Casas J, Machín J, Durán JJ, Serrano E, Cuchi JA, Mink S.
850 2008. Soil characteristics on varying lithological substrates in the South Shetland
851 Islands, maritime Antarctica. *Geoderma* **144**: 123–139. DOI:
852 10.1016/j.geoderma.2007.10.011

- 853 Navas A, Gaspar L, Quijano L, López-Vicente, M, Machín J. 2012. Patterns of soil
854 organic carbon and nitrogen in relation to soil movement under different land uses
855 in mountain fields (South Central Pyrenees). *Catena* **94**:43-52. DOI: DOI:
856 [10.1016/j.catena.2011.05.012](https://doi.org/10.1016/j.catena.2011.05.012)
- 857 Navas A, Laute K, Beylich AA, Gaspar L. 2014. Variations of soil profile
858 characteristics due to varying time spans since ice retreat in the inner Nordfjord,
859 western Norway. *Solid Earth* **5**: 485–498. DOI: 10.5194/sed-6-91-2014
- 860 Navas A, Oliva M, Fernández J, Gaspar L, Quijano L, Lizaga I. 2017. Radionuclides
861 and soil properties as indicators of glacier retreat in a recently deglaciated
862 permafrost environment of the Maritime Antarctica. *Science of the Total*
863 *Environment* **609**: 192–204. <https://doi.org/10.1016/j.scitotenv.2017.07.115>
- 864 O'Brien RMG, Romans JCC, Robertson L. 1979. Three soil profiles from Elephant
865 Island, South Shetland Islands. *British Antarctic Survey Bulletin* **47**: 1-12
- 866 Oliva M, Hrbáček F, Ruiz-Fernández J, De Pablo MA, Vieira G, Ramos, M, Antoniades
867 D. 2017b. Active layer dynamics in three topographically distinct lake catchments
868 in Byers Peninsula (Livingston Island, Antarctica). *Catena* **149**(2): 548–559. DOI:
869 [10.1016/j.catena.2016.07.011](https://doi.org/10.1016/j.catena.2016.07.011)
- 870 Oliva M, Navarro FJ, Hrbáček F, Hernández A, Nývlt D, Pereira P, Ruiz-Fernández J,
871 Trigo R. 2017a. Recent regional cooling of the Antarctic Peninsula and its impacts
872 on the cryosphere. *Science of the Total Environment*, DOI:
873 [10.1016/j.scitotenv.2016.12.030](https://doi.org/10.1016/j.scitotenv.2016.12.030)
- 874 Oliva M, Ruiz-Fernández J. 2015. Coupling patterns between para-glacial and
875 permafrost degradation responses in Antarctica. *Earth Surface Processes and*
876 *Landforms* **40**(9): 1227–1238. DOI: 10.1002/esp.3716

- 877 Otero XL, Fernández S, de Pablo MA, Nizoli EC, Quesada A. 2013. Plant communities
878 as a key factor in biogeochemical processes involving micronutrients (Fe, Mn, Co,
879 and Cu) in Antarctic soils (Byers Peninsula, maritime Antarctica). *Geoderma* **195-
880 196**: 145–154. DOI: 10.1016/j.geoderma.2012.11.018
- 881 Pereira A, Putze J. 1994. Floristic composition of Stinker Point, Elephant Island.
882 Antarctica. *Korean Journal of Polar Research* **5**(2): 37-47
- 883 Pereira TTC, Schaefer CEGR, Ker JC, Almeida CC, Almeida ICC. 2013.
884 Micromorphological and microchemical indicators of pedogenesis in Ornithogenic
885 Cryosols (Gelisols) of Hope Bay, Antarctic Peninsula. *Geoderma* **193-194**: 311–
886 322. DOI: 10.1016/j.geoderma.2012.10.023
- 887 Quayle WC, Peck LLS, Peat H, Ellis-Evans JC, Harrigan PR. 2002. Extreme responses
888 to climate change in Antarctic lakes. *Science* **295**, pp. 645. DOI:
889 10.1126/science.1064074
- 890 Quesada A, Camacho A, Rochera C, Velázquez D. 2009. Byers Peninsula: a reference
891 site for coastal, terrestrial and limnetic ecosystem studies in maritime Antarctica.
892 *Polar Science* **3**: 181–187. DOI: 10.1016/j.polar.2009.05.003
- 893 Ruiz-Fernández J, Oliva M. 2016. Relative paleoenvironmental adjustments following
894 deglaciation of the Byers Peninsula (Livingston Island, Antarctica). *Arctic,
895 Antarctic and Alpine Research*, **48**(2): 345–359. DOI: 10.1657/AAAR0015-014
- 896 Ruiz-Fernández J, Oliva M, García-Hernández C. 2017. Topographic and
897 geomorphologic controls on the distribution of vegetation formations in Elephant
898 Point (Livingston Island, Maritime Antarctica). *Science of the Total Environment*
899 **587-588**: 340-349. DOI: 10.1016/j.scitotenv.2017.02.158

- 900 Serrano E, López-Martínez J, Cuchi JA, Durán JJ, Mink S, Navas A. 2008. Permafrost
901 in the South Shetland Islands (maritime Antarctica): spatial distribution pattern. In
902 Kane D, Hinkel K. (eds), Proceedings Ninth International Conference on
903 Permafrost, University of Alaska Press, Fairbanks, t- 1, pp. 1621–1625
- 904 Serrano E, Martínez de Pisón E, López-Martínez J. 1996. Periglacial and nival
905 landforms and deposits. In López-Martínez J, Thomson MRA, Thomson, JW.
906 (eds), Geomorphological Map of Byers Península, Livingston Island. *BAS*
907 *GEOMAP Series, Sheet 5-A*, 1:25.000, with supplementary text. Cambridge, British
908 Antarctic Survey, pp. 28-34.
- 909 Serrano E, López-Martínez, J, Navas A. 2010. Stone fields and patterned ground
910 development on platforms in Elephant Island, maritime Antarctica. Third European
911 Conference on Permafrost. Thermal state of frozen ground in a changing climate
912 during IPY. EUCOP III, The University Centre in Svalbard (UNIS)
- 913 Simas FNB, Schaefer CEGR, Melo VF, Guerra MBB, Saunders M, Gilkes RJ. 2006.
914 Clay-sized minerals in permafrost-affected soils (Cryosols) from King George
915 Island, Antarctica. *Clays and Clay Minerals* **54**: 721–736- DOI:
916 <https://doi.org/10.1346/CCMN.2006.0540607>
- 917 Simas FNB, Schaefer CEGR, Melo VF, Albuquerque-Filho MR, Michel RFM, Pereira
918 VV, Gomes MRM, Costa LM. 2007. Ornithogenic cryosols from Maritime
919 Antarctica: Phosphatization as a soil forming process. *Geoderma* **138**: 191–203
- 920 Simas FNB, Schaefer CEGR, Albuquerque-Filho MR, Francelino MR, Filho EIF, Costa
921 LM. 2008. Genesis, properties and classification of cryosols from Admiralty Bay,
922 maritime Antarctica. *Geoderma* **144**: 116–122. Soil Survey Staff, 2014a. Keys to
923 Soil Taxonomy. 12th ed - DOI: 10.1016/j.geoderma.2006.11.011

- 924 Smith HG. 1972. The terrestrial Protozoa of Elephant Island, South Shetland Islands.
925 *British Antarctic Survey Bulletin* **31**: 55–62
- 926 Soto J, Navas A. 2004. A model of ^{137}Cs activity profile for soil erosion studies in
927 uncultivated soils of Mediterranean environments. *Journal of Arid Environments*
928 **59**: 719-730. <https://doi.org/10.1016/j.jaridenv.2004.02.003>
- 929 Souza KKD, Schaefer CEGR, Simas, FNB, Spinola DN, Paula MD, 2014. Soil
930 formation in Seymour Island, Weddell Sea, Antarctica. *Geomorphology* **225**: 87–
931 99. DOI: 10.1016/j.geomorph.2014.03.047
- 932 Tatur A, Barczuk A. 1985. Ornithogenic phosphates on King George Island, Maritime
933 Antarctic. In Siegfried WR, Condy PR, Laws RM (eds), Berlin. *Antarctic Nutrient*
934 *Cycles and Food Webs*. Springer-Verlag, pp. 163–169
- 935 Tatur A, Myrcha A. 1984. Ornithogenic soils on King George Island, South Shetland
936 Islands (Maritime Antarctic Zone). *Polish Polar Research* **5**(1-2): 31-60
937 <https://link.springer.com/article/10.1007/BF00239153>
- 938 Trouw RAJ, Ribeiro A, Paciullo FVP. 1991. Structural and metamorphic evolution of
939 the Elephant Island group and Smith Island, South Shetland Islands. In Thomson,
940 MRA, Crame JA, Thomson JW. (eds), UK, *Geological Evolution of Antarctica*.
941 Cambridge University Press, pp. 423–428.
- 942 Trouw RAJ, Passchier CW, Valeriano CM, Simões LSA, Paciullo FVP, Ribeiro A.
943 2000. Deformational evolution of a Cretaceous subduction complex: Elephant
944 Island, South Shetland Islands, Antarctica. *Tectonophysics* **319**: 93–110. DOI:
945 10.1016/S0040-1951(00)00021-4)
- 946 Turner J, Lu H, White I, King JC, Phillips T, Scott Hosking J, Bracegirdle TJ, Marshall
947 GJ, Mulvaney R, Deb P. 2016. Absence of 21st century warming on Antarctic

- 948 Peninsula consistent with natural variability. *Nature* **535**: 411-415.
 949 <http://dx.doi.org/10.1038/nature18645>
- 950 Turner J, Overland JE, Walsh JE. 2007. An Arctic and Antarctic perspective on recent
 951 climate change. *International Journal of Climatology* **27**: 277–293- DOI:
 952 10.1002/joc.1406
- 953 Turner J, Pendlebury S. 2004. *The International Antarctic weather forecasting*
 954 *handbook*. Cambridge: British Antarctic Survey, 663 pp.
 955 <http://nora.nerc.ac.uk/id/eprint/17324>
- 956 Ugolini FC. 1972. Ornithogenic soils of Antarctica. In Llano GA (ed), *Antarctic*
 957 *Terrestrial Biology*. Antarctic Research Series, pp. 181–193.
 958 DOI: 10.1002/9781118664667.ch9
- 959 Walton DWH. 1984. The terrestrial environment. London. In Laws RM (ed), *Antarctic*
 960 *Ecology*. Academic Press, pp. 1-60
- 961 Wilhelm KR, Bockheim JG, Haus NW. 2016. Properties and processes of recently
 962 established soils from deglaciation of Cierva Point, Western Antarctic Peninsula.
 963 *Geoderma* **277**: 10–22. DOI: 10.1016/j.geoderma.2016.05.001
- 964 Wilson MJ, Bain DC. 1976. Occurrence of *leucophosphite* in a soil from Elephant
 965 Island, British Antarctic Territory. *American Mineralogist* **61**: 1027-1028
- 966 Wilson MJ, Bain DC. 1986. Spheniscidite, a new phosphate mineral from Elephant
 967 Island, British Antarctic Territory. *Mineralogical Magazine* **50**: 291-293
 968 <http://jglobal.jst.go.jp/en/public/20090422/200902098113077974>
- 969 Wordie, J. (1922). II.—Shackleton Antarctic Expedition, 1914–1917 : Geological
 970 Observations in the Weddell Sea Area. Transactions of the Royal Society of
 971 Edinburgh, 53(1), 17-27. doi:10.1017/S0080456800004531

972

973

974

975

976

977

978 Table 1. Surface deposits, landforms and their altitudinal distribution in ice-free areas of
 979 Elephant Island. The characteristics of the permafrost are those at the study sites being
 980 related to their specific altitudes, which are indicated in the text.

981

Surface deposits	Landforms	Altitude m a.s.l.	Permafrost (at the study sites)
Till	Moraines	2- 140	Continuous
	Drumlin		Discontinuous
	Patterned ground		
	Gelifluction lobes		
	Frost mounds		
Weathering deposits	Stone fields	30-65	Continuous
	Patterned ground		Discontinuous
	Gelifluction sheets		
	Gelifluction lobes	0-140	Continuous
	Marine platforms		
Beach sediments	Raised beaches	0-10	Sporadic
Colluvium	Debris cone	0-45	Sporadic
	Debris talus		
Alluvium	Alluvial fan	0-30	Sporadic

982

983

984

Table 2. Location of the study sampling points, percentage and type of the vegetation cover and landforms.

	Location	Altitude m a.s.l.	Slope °	Orientation	Vegetation % aprox.	Landforms
A1	61° 13' 414 S 55° 21' 495 W	90	1°	W	80 Moss carpets	Moraine of the LIA intramorainic depression
A2	61° 13' 497 S 55° 21' 502 W	68	2°	NE	75 Moss	Coll on the upper part of platform
A3	61° 13' 410 S 55° 21' 750 W	60	4°	S	60 Moss	Erosive plain on the lower part of the intermediate platform
A4	61° 13' 644 S 55° 21' 719 W	30	3°	SE	10 Moss carpets	Moraine of the LIA on Holocene beaches
B1	61° 13' 841 S 55° 21' 831 W	90	1°	W	0	Drumlin, Hill
B2	61° 14' 093 S 55° 21' 605 W	60	4°	S	30 Mosses and Algae	Platform with nesting
B3	61° 14' 063 S 55° 21' 539 W	30	6°	NW	20 Algae and mosses	Moraines on the beaches Abandoned nesting
L	61° 6' 764 S 55° 26' 930 W	140	2°	W	20 Lichens	Marine platform Non or minimum ornithogenic activity

Table 3. Basic statistics for the main properties assayed in soils on moraines and platforms.

		Moraine n=13			Platform n=19			P-
		mean	SD	CV %	mean	SD	CV %	value
Grain Size < 2								
mm								
Sand	%	16.61	14.56	87.6	42.94	20.29	47.3 *	0.0004
Silt	%	72.51	12.02	16.6	49.70	18.53	37.3 *	0.0005
Clay	%	10.88	3.23	29.7	7.36	2.40	32.65 *	0.0013
Grain Size > 2								
mm								
> 12.5 mm	%	21.16	12.02	56.8	16.70	14.91	89.3	0.3768
6.3 – 12.5 mm	%	7.48	2.46	32.9	9.12	2.88	31.5	0.1048
2 – 6.3 mm	%	10.41	2.79	26.7	16.13	7.35	45.6 *	0.0123
< 2 mm	%	60.94	10.31	16.9	58.05	17.57	30.3	0.5988
Properties								
CO ₃ ⁼	%	0.46	0.36	79.5	0.21	0.09	46.9 *	0.0085
EC	dS m ⁻¹	0.13	0.11	87.2	0.13	0.23	178.1	0.9616
pH		7.71	0.88	11.5	5.17	1.32	25.6 *	0.0000
Nutrients								
SOC	%	0.280	0.284	99.2	0.558	0.312	55.6 *	0.0143
N	%	0.04	0.06	141.9	0.16	0.09	54.8 *	0.0002
SOC/SON ratio		8.39	1.87	22.3	5.49	5.33	97.1	0.0706
P ₂ O ₅	mg kg ⁻¹	387.69	1022.89	263.8	133.32	102.04	76.5	0.2868
K	mg kg ⁻¹	72.93	35.88	49.2	207.51	118.76	57.2 *	0.0004

Bold numbers are significant at the 95% confidence level.

SD: standard deviation, CV: coefficient of variation.

Table 4. Basic statistics for the stable elements (mg kg^{-1}) and mass activity of the natural and artificial radionuclides (Bq kg^{-1}) assayed in soils on moraines and platforms. Significant differences were considered at a $p < 0.05$.

Stable elements (mg kg^{-1})	Moraines n=13			Platforms n=19			P-value
	mean	SD	CV %	mean	SD	CV %	
Al	50073.3	2100	4.2	49291.4	2568.4	5.2	0.3710
Fe	45920.7	4635.2	10.1	45653.5	2759.8	6.1	0.8393
Ca	31601.5	1237.74	3.9	28856.4	4714.3	16.3	0.0512
Na	21287	3273.46	15.4	24302.2	3441.9	14.2	* 0.0189
Mg	5030.2	802.9	16	4544.6	731.5	16.1	0.0864
K	7622.7	1307.8	17.2	7717.7	1889.3	24.5	0.8763
Mn	1125.7	191.9	17.1	1181.7	403.8	34.2	0.6462
Pb	206.8	9.3	4.5	208.6	16.3	7.8	0.7233
Ba	187.9	105.1	55.9	384.9	496.6	129.1	0.1711
Sr	183.5	22.5	12.3	180.4	30.1	16.7	0.7568
Zn	70.1	6.1	8.7	94.7	47.5	50.2	0.0743
Cr	65.6	6.7	10.2	57.7	24.9	43.1	0.2712
Cu	47.4	6.8	14.3	28.8	14.4	50.1	* 0.0002
Li	35.3	1.6	4.5	36.1	6.6	18.3	0.6842
Co	25.9	4.1	15.9	15.9	6.3	39.3	* 0.0000
Ni	21.8	3.2	14.8	12.9	5.3	41.4	* 0.0000
Cd	1.47	0.27	18.3	1.51	0.94	61.9	0.8696
Radionuclides (Bq kg^{-1})							
^{137}Cs	0.05	0.16	360.6	1.28	3.43	268.8	0.208
$^{210}\text{Pb}_{\text{ex}}$	3.04	3.52	115.8	5.11	7.09	138.7	0.3379
^{226}Ra	14.72	1.04	7.1	16.55	4.73	28.5	0.1802
^{232}Th	16.12	0.83	5.2	17.89	4.76	26.6	0.1976
^{238}U	20.93	2.89	13.8	21.23	5.97	28.1	0.8642
^{40}K	327.77	39.05	11.9	402.47	210.85	52.4	0.2186

Bold numbers are significant at the 95% confidence level.

SD: standard deviation, CV: coefficient of variation.

Figure captions

Figure 1.- Maps of the South Shetland Islands in maritime Antarctica (A, B, C) and location of the study sites at Stinker Point and Lindsey Cape in Elephant Island (C, D). Map of the main geomorphological units, landforms and periglacial features at Stinker Point area (E).

Figure 2.- Location of the study soil profiles, diagrams of the sampled soil profiles on moraines and platforms and photographs of selected sampling sites and landforms.

Figure 3.- Distribution of the percentages of the coarse ($> 2\text{mm}$) and fine ($< 2\text{mm}$) fractions, contents of sand, silt and clay in the depth intervals of the study soils and vertical variations of carbonate percentages, electrical conductivity and pH and of soil nutrients contents: SOC, SON and extractable P and K in the soil profiles on moraines and platforms.

Figure 4.- Vertical distribution of the mean values of the stable elements (mg kg^{-1}) in the soil profiles on moraines and platforms.

Figure 5.- Vertical variations of the mass activities (Bq kg^{-1}) of fallout ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ and of the environmental radionuclides (^{40}K , ^{226}Ra , ^{238}U , ^{232}Th) in the study profiles of moraines and platforms.

Figure 6. 3D scatter plot diagram of the Principal Component Analyses including all the study parameters differentiating soils on moraines and platforms and 3D plots of main components weights showing vectors of all soil properties, stable elements and radionuclides for soils on moraines and platforms.