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SOIL SCIENCE

Soil-landform-vegetation interplays at Stinker Point, Elephant Island, Antarctica

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Abstract: The geomorphic dynamics on ice-free areas are crucial for understanding soil formation, vegetation and landscape stability in maritime Antarctic. We aimed to describe the soil formation on different landforms, following the Holocene glacial retreat at Stinker Point. Twenty profiles were sampled and classified, grouped into three landforms units: middle platforms and scarps, till/glacial deposits and present/Holocene raised beaches. Soil chemical and physical attributes were determined, and the vegetation type identified and quantified. Soils from till and glacial deposits can be separated by the age of exposure: older soils are stony, skeletic; and recently exposed till has soils with moderate depth, alkaline reaction and very high base saturation. Soils at the middle platforms are shallow, coarse-grained, skeletic, with abundant vegetation. Soils from the present-day beaches are alkaline, very coarse with no horizon differentiation, whereas soils on Holocene beaches are acid and nutrient-rich due to past or present-day influence of fauna. Soils from Stinker Point are generally shallow, skeletic and strongly related to the landforms and biogenic influences. Compared with other islands of the South Shetlands, in Elephant Island soil development is less pronounced, being this mainly attributed to the metamorphic nature of parent material, with greater resistance to weathering.

Key words: Cryosol, Holocene landscape, lichens, mosses, ornithogenic soils, platforms.

INTRODUCTION

Elephant Island is a remote island located around 61°10'S–55°10'W, in the south of the Drake Passage. Considered as part of the South Shetlands archipelago, its name is attributed to the presence of elephant seals colonies. The early sightings were reported by Captain George Powell in 1821, and are famous for having sheltered the men of the 1914 expedition led by Sir Ernest Shackleton, which was an extraordinary survival history in the glorious days of Antarctic exploration.

Set close to the southernmost border of the Scotia Arc, the island is basically composed by schists, derived from a Mesozoic–Cenozoic subduction complex, contrasting with other islands from the South Shetlands archipelago (Trouw et al. 1998, Dalziel et al. 2013). Outcrops show increasing metamorphism degree from NE to SW alignment and the foremost foliation presents E–W to NE–SW alignment mostly parallel to surface, among zones of orthogonal orientation (Trouw et al. 1991, 1998, 2000).

The first records of soils from Elephant Island came from fieldwork performed by O'Brien et al. (1979) in 1970-1971, which reported little mineral weathering and limited profile development, although modified by varying degrees of frost action. Wilson & Bain (1976) described leucophosphite related to the guano interaction with silicate minerals in samples from the same expedition, representing one of the pioneer reports on phosphatized soils in Antarctica.

Allison & Smith (1973) offered a first glance at extensive areas of ice-free ground with an unexpectedly wide range of habitats in which extensive plant communities developed, wherever melting water and some degree of shelter from the wind was afforded. The authors gave a detailed description and properly classified the vegetation communities occurring on headlands and raised marine terraces and platforms on the island southern coast (Allison & Smith 1973). Pereira & Putzke (1994) presented the floristic composition of Stinker Point as one of the first contributions of the Brazilian Antarctic Program in the island. These authors identified coarse soil enriched by faunal activity as an important substrate for flowering plants. The survey revealed the diversity of the vegetation cover reporting over 37 species of plants (the two native phanerogams *Deschampsia antarctica* and *Colobanthus quitensis* and 35 bryophytes) and 54 species of lichens (Pereira & Putzke 1994). The fauna is represented by a large number of marine mammals (weddell seals, antarctic fur seals, southern elephant seals); large colonies of penguins (*Pygoscelis papua* and *P. antarcticus*) and numerous nests of giant southern petrels (*Macronectes giganteus*), skuas (*Stercorarius antarcticus*) and other birds (Petry et al. 2018).

The paraglacial environments from of Maritime Antarctica with permafrost are sensitive to climate change, which can expose new areas to vegetation colonization and modify the soil formation (Bockheim et al. 2013, Navas et al. 2017). The investigations of accelerated geomorphic dynamics in such ice-free areas are crucial for understanding soil formation, vegetation establishment and landscape stability (Balks et al. 2013, Michel et al. 2014, Turner et al. 2016). López-Martínez et al. (2012) have identified the geomorphological features and mapped eight different periglacial landforms at 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) (Navas et al. 2018).

This study aims to describe the formation of soils and compare it with the vegetation cover on different landforms, following the Holocene glacial retreat at Stinker Point, Elephant Island. Thus, we hypothesize that vegetation cover and soils would be more developed in stable landforms with ice-free ground for longer exposure time, which had great faunal activity in the past.

MATERIALS AND METHODS

Study area

Elephant Island is the northernmost island in the South Shetlands archipelago (Fig. 1), with approximately 1400 km^2 (Allison & Smith 1973). It is covered by glaciers with only 5% of its area being ice-free (Navas et al. 2018), and Stinker Point, at the western shore is one of the largest ice-free areas. The morphology combines stable periglacial landforms with recently exposed surface, including platforms, beaches, strandflats, morainic complexes and glaciers (López-Martínez et al. 2012, 2016). Lithology comprises a metamorphic succession containing grey, green and blue phyllites and schists and layers of amphibolite and fine volcanic metaconglomerate (e.g. Marsh & Thompson 1985, Trouw et al. 1991). Trouw et al. (2000) identified a metamorphic succession with increasing intensity from northeast to southwest, Stinker

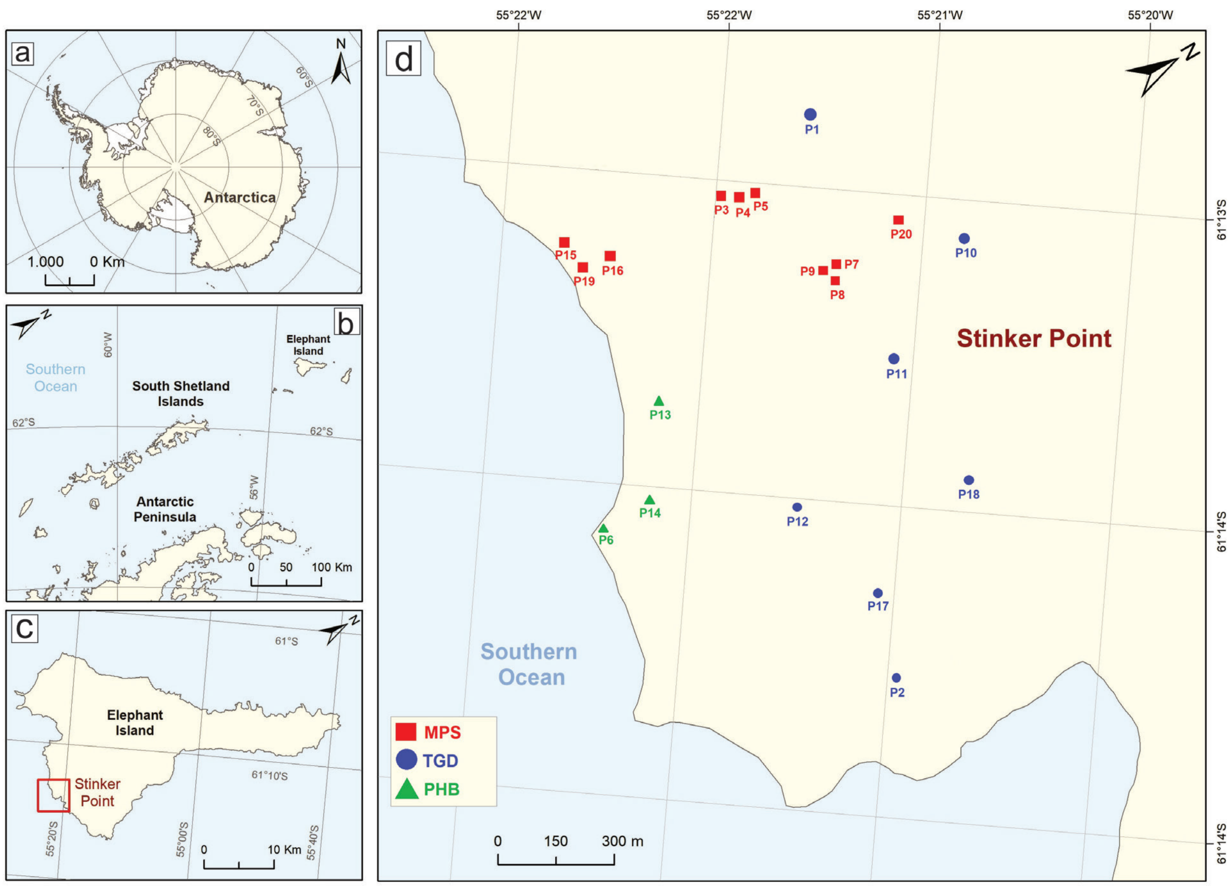

Figure 1. Location of the study area: Antarctica (a), South Shetland Islands (b), Elephant Island (c), Stinker Point with 20 sampled profiles (d).

Point belonging to the intermediate blueschist facies. In addition to the island location in the framework of the Scotia-Antarctic-South Shetland Block triple junction, glacioisostatic and neotectonic uplift have played a major role in shaping the landscape (Galindo-Zaldívar et al. 2006, López-Martínez et al. 2006, Abakumov et al. 2017).

The region experiences a sub-Antarctic cold, moist, maritime climate, with mean air temperature ranging from -10 °C to 1 °C (Turner & Pendlebury 2004) and means summer air temperatures above 0 °C (Rakusa-Suszczewski 1993). Precipitation is abundant, compared to the rest of the archipelago and ranges between 500 and 800 mm per year (Øvstedal & Lewis-Smith 2001). Permafrost is regarded as sporadic or inexistent in altitudes below 20 m a.s.l. and occurs discontinuously in altitudes from 30 to 150 m a.s.l. (Serrano & López-Martínez 2000, Vieira et al. 2010, Bockheim et al. 2013). Freeze-thaw cycles are common and occur in daily periods (Turner et al. 2007).

Landforms and related processes were described during fieldwork based on the regional reference of López-Martínez et al. (2012) updated by Navas et al. (2018). Navas et al. (2018) reported eight glacial landforms (till, glacier among others) eight periglacial and nival landforms, three fluvial and lacustrine and two marine landforms and deposits (present-day and Holocene beaches, middle platforms and scarps) (Fig. 2) that were used to guide this work.

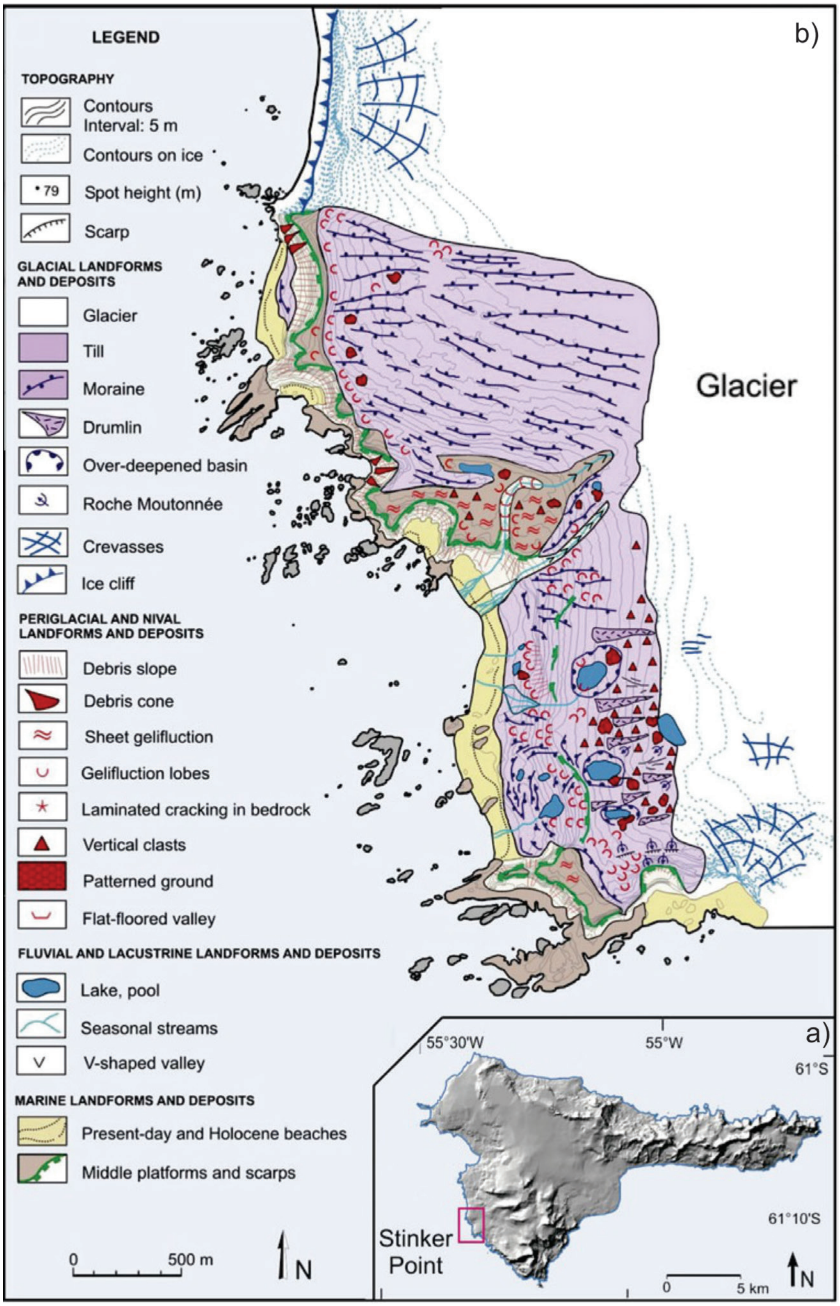

Figure 2. Map of the main geomorphological units, landforms, and periglacial features at Stinker Point area (b) in Elephant Island (a) (source Navas et al. 2018).

Soil characterization

Soil sampling was performed during the austral summer, in January and February of 2016. Twenty profiles distributed across Stinker Point were dug, sampled and analyzed down to the lithic contact or to the permafrost table (Table I). Soil profiles were grouped according to the landforms and landscape elements identified by López-Martínez et al. (2012) and Navas et al. (2018): till/glacial deposit (TGD); middle platforms and scarps (MPS); and present-day/Holocene beaches (PHB) (Fig. 3). We considered permafrost to be present (discontinuous) at middle platforms and till/glacial deposit (continuous) and sporadic at present-day/Holocene beaches. Seven profiles were located and collected at TGD: P1, P2, P10, P11, P12, P17 and

P18 (Table II); ten profiles were located at MPS: P3, P4, P5, P7, P8, P9, P15, P16, P19 and P20; and three were at PHB: P6, P13 and P14.

The morphology of the profile was described, and samples of soil horizons were collected following Bockheim et al. (2006). Soil classification followed the World Reference Base for Soil Resources (IUSS Working Group WRB 2015). Soil properties were measured at the soil laboratory, following international standard protocols (EMBRAPA 2017). Soil texture was analyzed by mechanical dispersion of <2 mm samples in distilled water, sieving and weighting of the coarse and fine sand, sedimentation of the silt fraction followed by siphoning of the <2 µm fraction (Gee & Bauder 1986). Soil textural classes were determined using a soil textural chart (Sand 0.05-<2mm, silt 0.002-<0.05 mm and clay < 0.002 mm). The pH in water and KCl were determined using the ratio soil:liquid 1: 2.5; acidic components (H + Al) were extracted with $Ca(OAc)_2$ 0.5 mol L^{-1} buffered to pH 7.0 and quantified via titration with NaOH 0.06 mol L^{-1}. Exchangeable Ca, Mg, and Al were extracted with 1 mol L^{-1} KCl, and determined via atomic absorption spectroscopy. Available P, K, Na, Fe, Zn, Cu and Mn, were extracted with Mehlich-1 (0.05 mol L^{-1} HCl in 0.0125 mol L^{-1} H_2SO_4), and quantified using flame photometry. Element's concentrations in the extracts were determined by atomic absorption ($Ca^{2+,}$ Mg^{2+} and Al^{3+}), flame emission (K^+ and Na^{2+}) and photocolorimetry (P), microelements were determined using inductively coupled spectroscopy. Organic matter (OM) was determined by wet combustion with external heating (Yeomans & Bremner 1988). We also evaluated the capacity of soils to adsorb P (P-rem) by shaking 2.5 g of soil for 1 h with 25 ml of 0.01 mol L^{-1} $CaCl_2$ containing 60 mg L^{-1} of P. The suspension was filtered and the P remaining in solution (P-rem) was measured by photocolorimetry (Alvarez et al. 2000).

Effective cation exchange capacity (CECeff) was calculated via determining the sum of cations (Ca^{2+}, Mg^{2+}, Na^+, K^+, and A^{3+}) whereas the total cation exchange capacity (CEC_T) was estimated using the bases sum (BS) and potential acidity (H+Al). We determined the percentage of base saturation (PSB) and aluminum saturation (Al_sat).

Vegetation classification and fauna activity

The vegetation surrounding the profile was collected and identified according to Ochyra et al. (2008) and Putzke & Pereira (2001); and evaluated the type of community according to Longton's classification (1988). The associations are characterized by codominant species or by restricted occurrence in more specific habitats (Schmitz et al. 2020a, b). The fauna activity was evaluated by observing the animals that inhabited the site at the time of collection of traces found (nests, bones, guano).

Data analyses

Physical and chemical soil properties were summarized through a principal component analysis (PCA) on the correlation matrix using the 'FactoMineR' package (Husson et al. 2017). This analysis was applied to reduce the number of redundant soil properties and identify patterns of similarity between landforms samples (i.e. Schmitz et al. 2020a, b). We also calculated Pearson correlations among soil properties and the PCA ordination axes. The attributes with greater correlation in the PCA axes were used for descriptive analysis of the three landforms through boxplots. All analyses were carried out using the R environment (R Core Team 2021).

Table I. Location, soil classification and description of the areas (landscape and vegetation) of the 20 soil profiles (P) sampled at Stinker Point.

P	Elev m a.s.l.	Geographic position	Classification WRB-FAO	Description	Vegetation type/common species
1	120	S 61°13'10.7" W 55°21'28.0"	Turbic Leptic Skeletic Cryosol (Dystric, Ornithic)	Till/glacial deposit in top; well drained; plan to soft wavy; no current presence of bird nests	Moss carpet community associated with fruticose lichens: *Sanionia uncinata, Polytrichastrum alpinum, Chorisodontium acyphillum, Usnea antarctica, Cladonia* sp., *Ochrolechia frigida, Himantormia lugubris, Psoroma* sp., *Prasiola crispa*
2	110	S 61°14'07.2" W 55°21'17.2"	Turbic Cryosol (Dystric, Ornithic)	Till/glacial deposit in top; well drained; flat to wavy relief; Skua nests nearby	Mixed community moss cushions-musciculous lichens association: *Andreaea* sp., *Bryum* sp., *Ochrolechia frigida*, *Cystocoleus niger* and *Caloplaca* sp.
3	69	S 61°13'17.9" W 55°21'58.8"	Turbic Leptic Skeletic Cryosol (Dystric, Ornithic)	Middle platform, well drained; plan to soft wavy relief; Petrel and skua nests nearby	Moss carpet community associated with fruticose lichens: *Sanionia uncinata*, *Sphaerophorus globosus*, *Polytrichastrum alpinum*, *Chorisodontium aciphyllum*, *Cladonia borealis*, esporadic *Deschampsia* antarctica and *Prasiola crispa*.
4	65	S 61°13'18.0" W 55°21'58.1"	Turbic Leptic Skeletic Cryosol (Dystric, Arenic, Ornithic)	Middle platform, well drained; plan to soft wavy relief; Petrel and skua nests nearby	Moss carpet community: *Sanionia uncinata* with *Deschampsia antarctica*, esporadic *Chorisodontium aciphyllum*, and *Polytrichastrum alpinum* tufts.
5	60	S 61°13'17.9" W 55°21'57.0"	Turbic Leptic Cryosol (Dystric, Arenic)	Middle platform, well drained; plan to soft wavy; Skua nests and lake nearby;	*Deschampsia antarctica* phanerogamic community associated with *Sanionia uncinata*
6	4	S 61°13'46.8" W 55°21'46.3"	Dystric Arenosol (Gelic)	Present-day beaches, well drained, plan; presence of mammals and seabirds	Bare soil
7	60	S 61°13'24.2" W 55°21'34.8"	Turbic Leptic Skeletic Cryosol ("Patterned", Dystric, Ornithic)	Middle platform, well drained; plan to soft wavy; occasional skuas and petrels	Moss turf community *Chorisodontium aciphyllum* associated with lichens: *Sphaerophorus globosus*, *Cladonia borealis*, *Ochrolechia frigida*, *Usnea antarctica*, *Psoroma* sp., *Sanionia uncinata.*
8	60	S 61°13'23.8" W 55°21'34.3"	Turbic Leptic Skeletic Cryosol ("Patterned", Dystric, Ornithic)	Middle platform, well drained; plan to soft wavy; occasional skuas and petrels	Moss carpet community *Sanionia georgicouncinata*
9	60	S 61°13'23.9" W 55°21'35.9"	Turbic Leptic Skeletic Cryosol ("Patterned", Eutric, Ornithic)	Middle platform, well drained; plan to soft wavy; occasional skuas and petrels	Fruticose lichens community: *Sphaerophorus globosus* associated with mosses: *Chorisodonthium acyphillum*, *Himantormia lugrubis*, *Usnea antarctica*, *Psoroma* sp., *Cladonia borealis*, *Cladonia rangiferina*, *Polytrichastrum alpinum*, *Sanionia uncinata*

Table I. Continuation.

10	52	S 61°13'24.3" W 55°21'04.0"	Turbic Cryosol ("Patterned", Eutric)	Till/glacial front and deposit; moderately drained; flat to wavy relief	Bare soil
11	48	S 61°13'36.5" W 55°21'16.9"	Turbic Leptic Cryosol ("Patterned", Eutric)	Till, glacial deposit; moderately drained; wavy relief; near lake; occasional skuas.	Moss cushion community *Bryum orbiculatifolium*, *Hennediella heimii* (fertile), *Brachythecium* sp.
12	50	S 61°13'50.1" W 55°21'27.5"	Turbic Leptic Cryosol ("Patterned", Eutric)	Till/glacial deposit; moderately drained; wavy relief; near drain line and lake; occasional skuas.	Moss cushion community *Bryum orbiculatifolium* and *Hennediella heimii*
13	22	S 61°13'33.1" W 55°21'37.5"	Eutric Regosol (Gelic, Ornithic, Turbic)	Holocene beaches, raised marine terrace; well drained; wavy relief; occasional seabirds.	Phanerogamic community *Colobanthus quitensis* associated with mosses *Sanionia uncinata* and *Polytrichastrum alpinum*
14	20	S 61°13'47.7" W 55°21'39.4"	Dystric Regosol (Gelic, Ornithic, Turbic)	Holocene beaches, raised marine terrace; well drained; wavy relief; occasional seabirds.	Phanerogamic community *Deschampsia antarctica*; *Caloplaca regalis* on the rocks
15	92	S 61°13'18.8" W 55°22'04.7"	Turbic Leptic Skeletic Cryosol (Eutric, Ornithic)	Middle platform, moderately drained; wavy relief; in *Pygocelis antarcticus* active rookery.	Bare soil
16	90	S 61°13'20.6" W 55°22'04.0"	Turbic Leptic Skeletic Cryosol (Dystric, Ornithic)	Middle platform, well drained, wavy relief, Petrel nests nearby, adjacent to P15 (penguin rookery).	Macroscopic alga community *Prasiola crispa*
17	55	S 61°13'57.6" W 55°21'12.9"	Turbic Leptic Cryosol ("Patterned", Eutric)	Till/glacial deposit; moderately drained; wavy relief; near lake; occasional skuas.	Moss cushion community *Bryum orbiculatifolium*, *Hennediella heimii*, *Brachythecium* sp.
18	58	S 61°13'51.7" W 55°20'59.1"	Turbic Cryosol ("Patterned", Eutric)	Till/glacial front and deposit; moderately drained; flat to wavy relief	Bare soil
19	70	S 61°13'21.0" W 55°22'07.2"	Turbic Leptic Skeletic Cryosol (Dystric, Arenic, Ornithic)	Middle platform; well drained, plan relief, Petrel and skuas nests nearby	Moss carpet community associated with musciculous lichens: *Sanionia uncinata*, *Andreaea* sp., *Usnea antarctica*, *Sphaerophorus globosus*, *Psoroma* sp., *Ochrolechia frigida*, *Cladonia* sp.
20	90	S 61°13'20.4" W 55°21'26.9"	Turbic Leptic Cryosol (Eutric, Arenic, Ornithic)	Middle platform, well drained, wavy relief, occasional seabirds	Moss carpet community associated with musciculous lichens: *Sanionia uncinata*, *Polytrichastrum alpinum*, *Usnea antarctica*, *Sphaerophorus globosus*, *Ochrolechia frigida*, *Cladonia* sp.

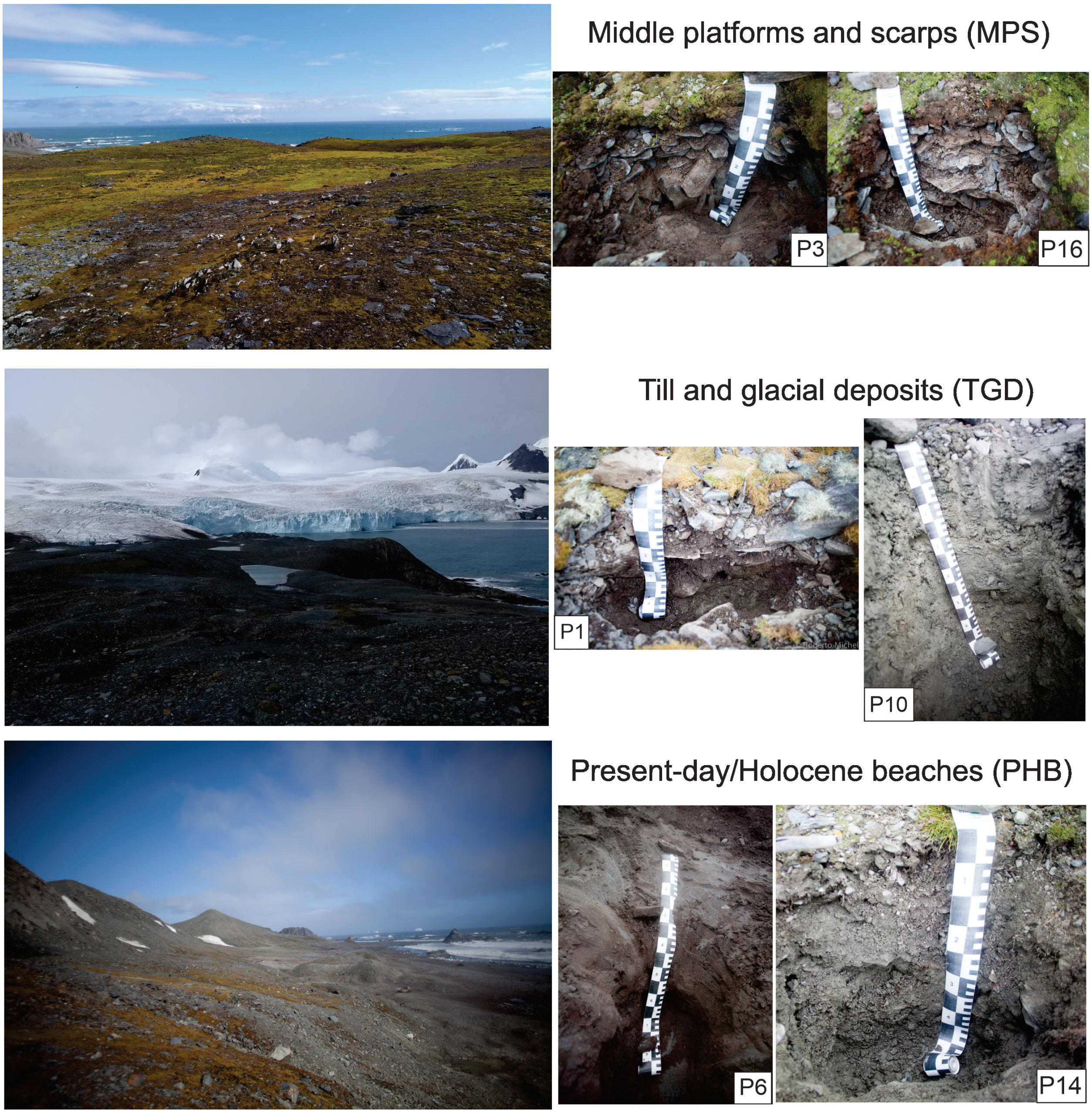

Figure 3. Landforms and representative soil profiles, sampled at Stinker Point: P3 and P16 Middle platforms and scarps, P1 (older soils) and P10 (recently exposed) at Till and Glacial deposit, Present day (P6) and Holocene beaches (P14).

RESULTS

General soil characteristics and main descriptors

Soils at Elephant Island were predominantly shallow and rich in coarse materials (Table II). Soils from recently exposed areas were alkaline and eutric (P10, P11, P12, P13, P17, and P18), whereas those soils from older areas were more developed, presented low pH and dystric character (P3, P4, P5, P8, P16, and P19), even when affected by faunal nutrient inputs (Table III). All soil structures were weak or moderate, fine or medium, and blocky or subangular

Table II. Temperature (T), color, physical properties and texture of the 20 soil profiles sampled in Stinker Point.

Horizons	Depth	T	Color (dry)		Gravel	Sand	Silt	Clay	Texture
	(cm)	(°C)			----------------------%--------------------				
Till/glacial deposit (TGD)									
P1 – Turbic Leptic Skeletic Cryosol (Dystric, Ornithic)									
A	5-15	8.0	10YR 3/2	Very dark grayish brown	85	74	19	7	Loamy sand
B	15-35+	5.9	2.5Y 4/2	Dark grayish brown	52	66	31	3	Sandy loam
P2 – Turbic Cryosol (Dystric, Ornithic)									
A	5-10	6.9	5Y 5/1	Gray	38	58	37	5	Sandy loam
B1	10-22	5.9	5Y 5/1	Gray	33	57	38	6	Sandy loam
B2	22-35	5.5	5Y 5/1	Gray	51	54	41	6	Sandy loam
C	35-48	5.0	5Y 5/1	Gray	38	51	35	5	Sandy loam
P10 - Turbic Cryosol ("Patterned", Eutric)									
C1	0-25	6.2	10Y 6/1	Greenish Gray	29	46.4	19.5	34.1	Clay loam
C2	25-50	5.3	7.5Y 5/1	Gray	37	52.8	39.8	7.4	Loam
C3	50-65+	5.0	7.5Y 5/1	Gray	44	51.5	41.8	6.7	Loam
P11 - Turbic Leptic Cryosol ("Patterned", Eutric)									
C1	0-10	8.3	7.5Y 5/1	Gray	54	57	39.3	3.6	Sandy loam
C2	10-20	5.5	7.5Y 5/1	Gray	48	51.6	38.6	9.8	Sandy loam
C3	20-35+	4.0	5Y 5/1	Gray	44	52.3	41.0	6.7	Sandy loam
P12 - Turbic Leptic Cryosol ("Patterned", Eutric)									
C1	0-12	8.6	7.5Y 5/1	Gray	51	52.5	38.4	9.8	Sandy loam
C2	12-40	5.0	5Y 5/1	Gray	63	49.9	40.2	9.9	Sandy loam
P17 – Turbic Leptic Cryosol ("Patterned", Eutric)									
C1	0-12	6.3	7.5Y 5/1	Gray	33	45.3	47.1	7.6	Loam
C2	12-35+	4.0	7.5Y 5/1	Gray	25	43	48.9	8.1	Loam
P18- Turbic Cryosol ("Patterned", Eutric)									
C1	0-10	12.0	7.5Y 5/1	Gray	35	51.5	44.6	4.0	Sandy loam
C2	10-22	5.4	7.5Y 5/1	Gray	38	42.8	51.4	5.9	Silt loam
C3	22-30	3.9	7.5Y 5/1	Gray	27	41.5	54.7	3.8	Silt loam

Table II. Continuation.

Middle platforms and scarps (MPS)									
P3 - Turbic Leptic Skeletic Cryosol (Dystric, Ornithic)									
A	0-12	5.6	7.5YR 3/1	Very Dark Gray	29	96.1	2.4	1.5	Sand
BC	12-40	4.9	7.5YR 4/2	Brown	65	78.7	8.1	13.3	Sandy loam
P4 – Turbic Leptic Skeletic Cryosol (Dystric, Arenic, Ornithic)									
A/O	3-6	6.8	5YR 3/1	Very Dark Gray	11	96.6	0.3	3.0	Sand
A	6-10	6.5	7.5YR 3/2	Dark Brown	33	96.9	1.6	1.5	Sand
BR	10-35+	4.6	7.5YR 4/2	Brown	57	86.7	6.1	7.2	Sand
P5 - Turbic Leptic Cryosol (Dystric, Arenic)									
A/01	0-8	5.7	7.5YR 3/1	Very Dark Gray	22	98.4	1.3	0.3	Sand
A/02	8-22	5.1	5YR 3/1	Very Dark Gray	10	99.1	0.7	0.2	Sand
B	22-40	4.8	7.5YR 4/2	Brown	54	88.7	5.3	6.0	Sand
P7 - Turbic Leptic Skeletic Cryosol ("Patterned", Dystric, Ornithic)									
A	0-10	4.3	2.5Y 4/1	Dark Gray	94	71.8	19.4	8.9	Sandy loam
AB	10-17	3.9	2.5Y 5/1	Gray	72	75.3	16.8	7.9	Sandy loam
B	17-40+	3.5	2.5Y 6/1	Gray	37	54.4	39.5	6.1	Loam
P8 - Turbic Leptic Skeletic Cryosol ("Patterned", Dystric, Ornithic)									
O	0-5	6.8	10YR 4/2	Dark Grayish Brown	32	77	12.9	10.1	Sandy loam
A	5-10	6.4	10YR 5/2	Grayish Brown	72	79	12.8	8.2	Sandy loam
BR	10-30	4.4	7.5 YR 5/2	Grayish Brown	79	76.3	18.1	5.6	Sandy loam
P9 - Turbic Leptic Skeletic Cryosol ("Patterned", Eutric, Ornithic)									
A	0-15	-	2.5Y 4/1	Dark Gray	97	75.8	11.2	13.1	Sandy loam
B	15-30	-	10YR 5/2	Grayish Brown	84	62.5	18.6	18.9	Sandy loam
P15 – Turbic Leptic Skeletic Cryosol (Eutric, Ornithic)									
A	0-12	7.6	10YR 5/2	Grayish Brown	90	55.6	30.1	14.3	Sandy loam
B	12-35+	6.4	10YR 5/2	Grayish Brown	91	54.8	28.2	17.1	Sandy loam
P16 – Turbic Leptic Skeletic Cryosol (Dystric, Ornithic)									
A	0-5	6.3	7.5YR 3/2	Dark Brown	80	68.6	14.7	16.7	Sandy loam
C1	5-15	5.0	10YR 5/2	Grayish Brown	72	68.1	21.0	10.9	Sandy loam
C2	15-40+	4.0	2.5Y 5/2	Grayish Brown	52	62.7	31.4	5.9	Sandy loam
C2 incl	25-35	-	7.5YR 4/3	Brown	25	64.6	27.9	7.4	Sandy loam

Table II. Continuation.

P19 - Turbic Leptic Skeletic Cryosol (Dystric, Arenic, Ornithic)									
O/A	0-12	6.8	2.5Y 3/1	Very Dark Gray (brownish)	73	75.9	15.8	8.4	Sandy loam
B	12-20	6.5	10YR 4/2	Grayish Yellow Brown	51	61.6	28.3	10.0	Sandy loam
C	20-40	-	2.5Y 5/2	Dark grayish yellow	51	55.3	31.8	13.0	Sandy loam
P20 - Turbic Leptic Cryosol (Eutric, Arenic, Ornithic)									
A	0-5	5.4	2.5Y 5/2	dark grayish yellow	54	75.2	22.8	2.0	Loamy Sand
B	5-15	4.4	5Y 5/1	Gray	45	72.4	27.1	0.6	Loamy Sand
C	15-40+	3.5	5Y 5/1	Gray	52	69.0	29.6	1.4	Sandy loam
Present-day/Holocene beaches (PHB)									
P6- Dystric Arenosol (Gelic)									
1A	0-25	-	5YR 3/1	Very Dark Gray	14	98.9	1.0	0.1	Sand
2B1	25-55	-	2.5YR 3/1	Gark Reddish Gray	3	99.3	0.4	0.3	Sand
2B2	55-70+	-	5YR 3/1	Very Dark Gray	5	99.2	0.7	0.0	Sand
P13 - Eutric Regosol (Gelic, Ornithic, Turbic)									
A	0-10	16.0	5Y 5/1	Gray	40	62.8	34.4	2.9	Sandy loam
B	10-28	10.0	5Y 5/1	Gray	38	68.3	28.4	3.3	Sandy loam
C1	28-45	6.8	5Y 5/1	Gray	38	65.7	32.2	2.1	Sandy loam
C2	45-60+	5.0	5Y 5/1	Gray	36	67.8	29.8	2.5	Sandy loam
P14 - Dystric Regosol (Gelic, Ornithic, Turbic)									
A	0-10	13.8	5Y 5/1	Gray	49	65.7	30.9	3.3	Sandy loam
B	10-25	12.1	5Y 6/1	Gray	45	61.8	33.8	4.4	Sandy loam
C1	25-45+	6.9	5Y 5/1	Gray	37	54.7	39.4	5.9	Sandy loam
Ex. samp	0-10	-	2.5Y 5/1	Gray	59	80.1	19.1	0.8	Loamy sand

blocky. Horizon transition was mainly gradual or diffuse with little horizon differentiation, probably by cryoturbation when the active layer in the soil can erode moving from the soil surface downwards as from permafrost upwards. However, during this process, patterned ground and gelifluction sheets are rare, whereas stone fields are more common due to the high parent material strength. Vegetation cover was abundant on most profiles being influenced by landscape stability, faunal colonization, and wind exposure. Stinker Point can be divided into two major landscapes, ones occupied by glaciers during the last glacial advance of the Little Ice Age, and areas that remained ice-free during this period; vegetation has just begun colonizing the first.

High variability in soil properties was observed in the three different landforms (Fig. 4). The chemical soil properties are explained by the first and two PCA axes with 61.3 % of the data variation (Fig. 4a). Thus, the first axis being positively correlated with the BS (r = 0.92), P (r = 0.89), Zn (r = 0.89) and Na (r = 0.86). The second axis being positively correlated with BS (r = 0.94) and Mn (r = 0.86). The PCA of physical soil properties (Fig. 4b) showed that the first PCA axis explained 68.5 % of the data and was positively correlated with silt fraction (r = 0.91) and negatively with a sand fraction (r = -0.99). The most accentuated gradient was verified in the soil acidity (pH and H + Al) (Fig. 4c), where the PCA Axis 1 explained 87.7 % of the variation in the soil data, and was positively correlated with exchangeable acidity (r = 0.93) and negatively with pH (r = -0.93).

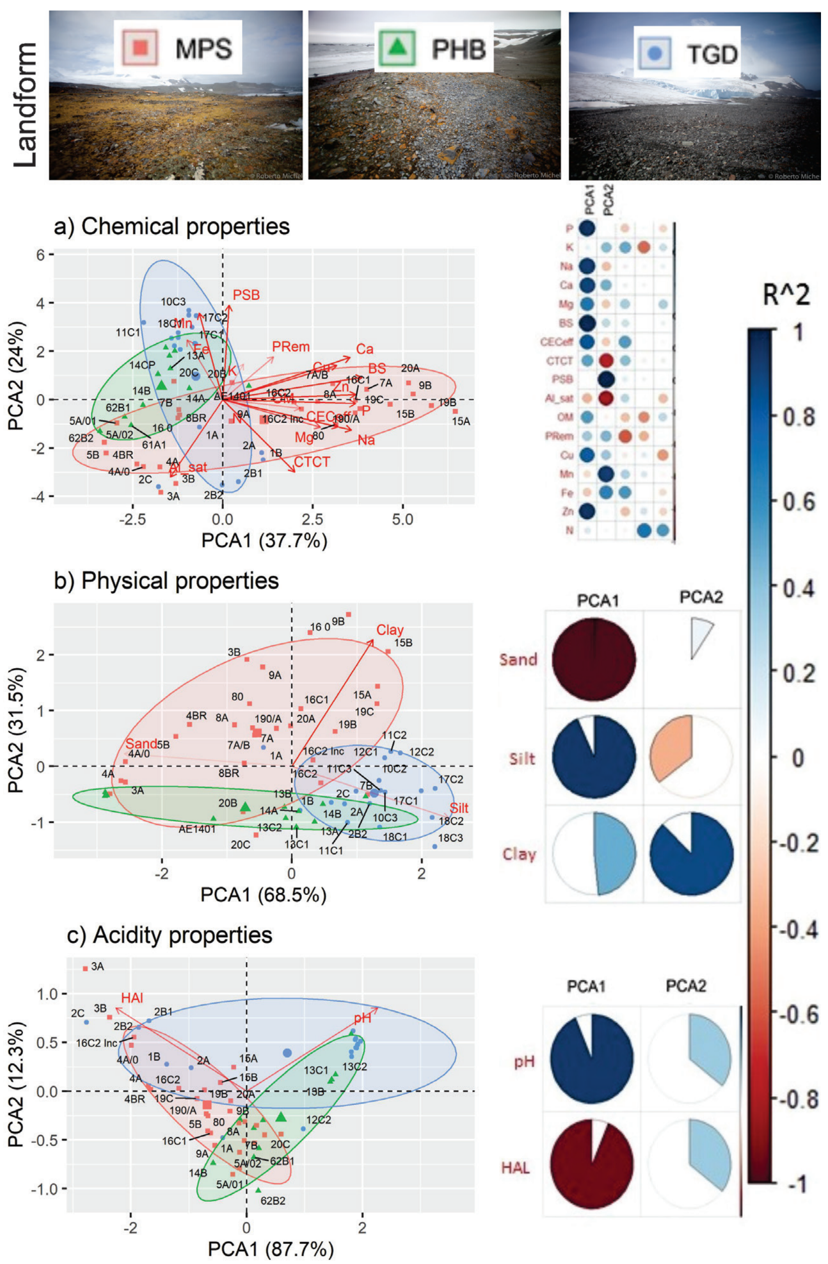

Figure 4. **Principal component analysis (PCA) for the soil parameters of three different landscapes elements: PHB: Present-day and Holocene beaches; MPS: Middle platforms and scarps; TGD: Till glacial deposit. For analysis, available: a) chemical properties (P, K, Na, Ca, Mg, Al, BS, CECeff, CTC_T, Zn, Cu, OM, N, Zn, Mn, PBS, Al_sat, N); b) physical properties (Sand, Silt and Clay); and c) Acidity properties (pH and H + Al).**

Middle platforms and scarps (MPS)

The soils were shallow and coarse, mostly with high P, Ca, and Mg contents, and low pH (Table III, Fig. 5). Cobles and boulders of various shapes, pebbles, and gravels are commonly observed; altitude varies from 60 to 70 m a.s.l. All profiles were well-drained and stone fields and snow patches are widespread. The degree of ornithogenic influence varies (all profiles being ornithic), but the middle platforms are the landscape more colonized by birds. All profiles were classified as Cryosols being always turbic and leptic, frequently patterned, dystric, and skelectic (IUSS Working Group WRB 2015). Few profiles were found to be eutric, only those affected by recent guano deposition, close to petrel nests (P7 and P20) or penguin rookery (P15). For representing the most stable landform at Stinker Point, all buildings are located on it,

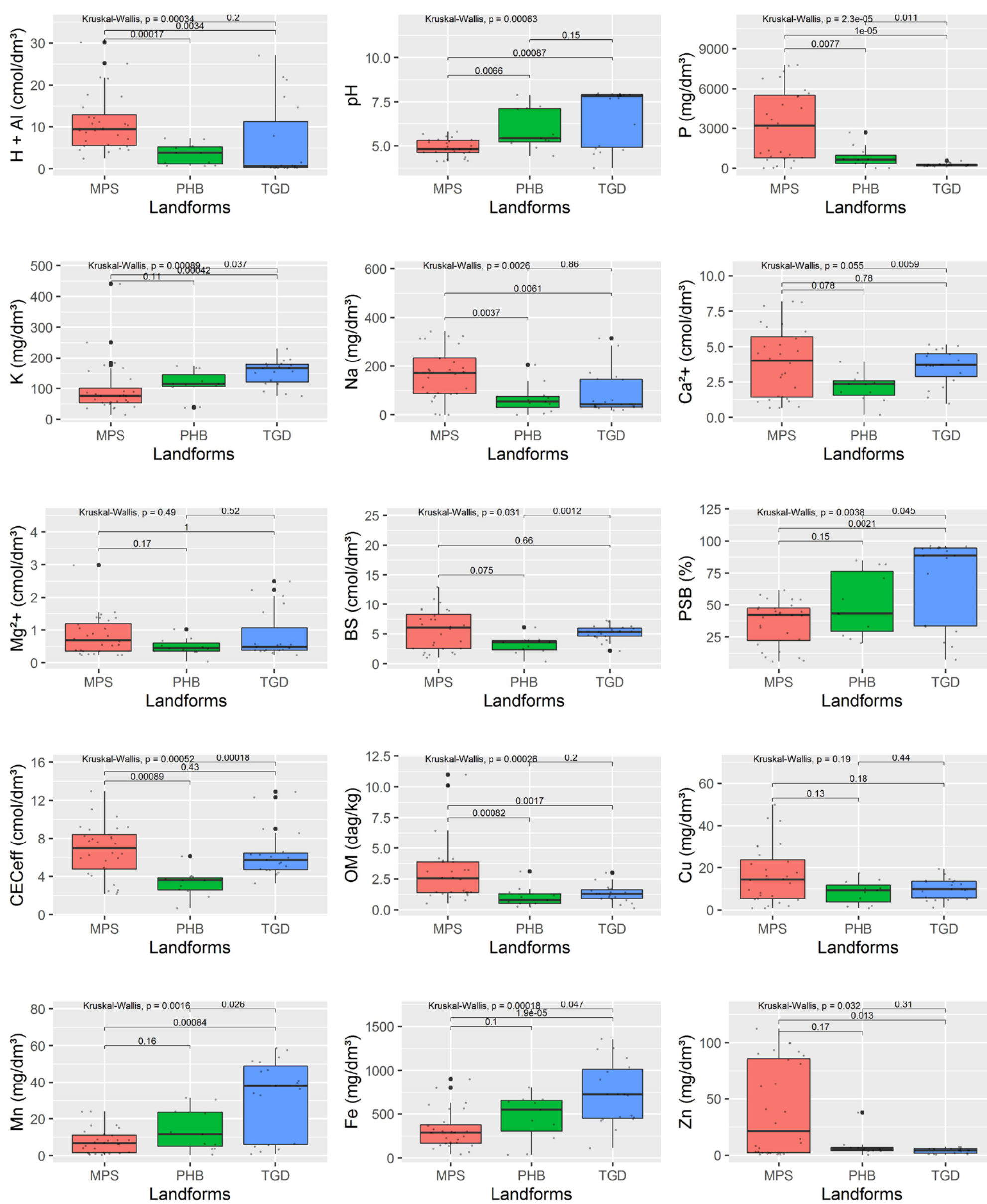

Figure 5. Boxplots soil properties. For analysis, available: exchangeable acidity (H + Al), pH (H_2O), phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), bases sum (BS), percentage of bases saturation (PSB), effective cation exchange capacity (CTCeff), organic matter (OM), copper (Cu), manganese (Mn), iron (Fe) and zinc (Zn).

despite the logistical challenges, of reaching these high grounds.

Soil structure is weak medium/small blocky, and texture is dominated by sand and silt fractions (Table II). Profiles presented acid pH and high P content, mainly in depth (Table III), meanwhile, K is more abundant in surface with low totals when compared to other nutrients, such as Ca and Mg that present high values (mean 3.87 cmol/dm^3 ±2.46 and 0.82 cmol/dm^3 ±0.60, respectively). Na^+ concentration varies depending on the wind exposure to marine sprays and can expressively reach more than 300 mg/dm^3 (P15 and P19). Cation exchange capacity (CECeff) was low to medium (mean 6.73 cmol/dm^3 ±2.79) and Al has a considerable percentage of charges (mean 1.06 cmol/ dm^3 ±1.76). Organic matter is always above 1 % in all horizons reaching more than 10 % in some cases (P8 and P19); although organic carbon resilience in the island can be limited due to soil texture and effective drainage. The remaining P (P-rem) was high for most of the profiles (mean 40.8 mg/L ±12.92) with high exchangeable P content (mean 3244.18 mg/dm^3 ±2724.68). The amounts of extractable microelements are variable; Zn rates were high (40.45 mg/dm^3 ±41.24) for most Cryosols, with remarkably higher values for ornithogenic soils. The Fe distribution is regular with depth for all profiles but the middle platforms support high iron contents, especially in the more weathered and deeper profiles (mean 319.36 mg/dm^3 ±217.10). On the other hand, ornithogenic soils reached values up to 902.2 mg/dm^3 (P4), suggesting ferrolysis. Copper contents were also more expressive in sites affected by intense bird colonization, and Mn amounts were relatively low (7.7 mg/dm^3 ±6.73) (Fig. 5).

All profiles located on the platforms were vegetated, except for P15, which had bare soil since it was located in an active penguin rockery area. Soils P3, P4, P7, P9, P19, and P20 had an abundant and diverse vegetation cover, formed by different species associations of mosses and lichens, and eventually with the sporadic presence of grass and terrestrial algae. The P5 had a dominant coverage of the grass *Deschampsia antarctica* associated with the moss *Sanionia uncinata*, with less occurrence. The P8 had an exclusive cover of *Sanionia georgicouncinata*, located in a small depression on the platform. Also, the P16, located in an area adjacent to an active penguin rookery of *Pygoscelis antarcticus* (P15) and nests of giant petrels (*Macronectes giganteus*), had a dominant coverage of macroscopic algae *Prasiola crispa*.

Till and glacial deposits (TGD)

Soils from the till and glacial deposits can be divided by the age of exposure: older skeletic profiles with limited depth (P1 and P2), acid reaction (pH ~ 4.5) and moderate contents of P (mean 378 mg/dm^3), OM (1.3 dag/Kg) and PSB (23.6 %); and recently exposed deep profiles (P10, P11, P12, P17, and P18) which showed fine texture, alkaline reaction (pH ~ 7.7) and high PSB (91.65 %). This contrast illustrates how the landscape at Stinker Point has been differentially exposed and weathered, aided by faunal activity and vegetation. P1 presented a well-developed vegetation cover formed by a moss carpet community associated with fruticose lichens species (Table I, Fig. 3); and P2, a mixed community formed by moss cushions associated with musciculous lichens, with many crusted lichens on exposed rocks.

On the other hand, the recently exposed ice-free zone forms extensive areas of Till, following the last deglaciation phase. These soils have an alkaline reaction increasing with depth, moderate amounts of P (187.62 mg/dm^3 ±45.23) and Na (mean 89.65 mg/dm^3), high Ca (4.19 mg/dm^3 ±0.73) (Fig. 5), and low Mg content.

Furthermore, these areas represent a typical paraglacial environment of Stinker Point that underwent alteration processes after becoming ice-free; it is a landscape of great instability, where cryoturbation processes are widespread (generating patterned ground), and active fluvioglacial erosion (especially in the channels emerging from the glacier). Soils showed high silt content (always above 30%), with textural classes from sandy loam or finer, turbic, patterned, and eutric (IUSS Working Group WRB 2015). The recently exposed soils at the glacier front (P10 and P18) are barelycovered. Soils near lakes and drainage lines, and constantly visited by birds (P11, P12, and P17) have a vigorous vegetation cover but discontinuous, with low diversity. The vegetation was represented by moss cushion communities with a dominance of species as *Bryum orbiculatifolium* and *Hennediella heimii* (Table I).

Present-day/Holocene beaches (PHB)

The soil from the present-day beaches (P6) was acid, very coarse with no horizon differentiation; it was formed over marine sand sediments, covered by debris from up slopes, connecting with the upper platforms. Nival landforms and processes dominate, including slow sediment transfer, weathering (wet-drying and freeze-thaw cycles), and frost cracking. Periglacial features or permafrost were not detected, and the landscape is constantly reworked by marine erosion. Weathered moraines and till deposits were overlaid of the present-day beaches, and are the preferred sites for fauna. Due to the intense trampling of soil by animals, the vegetation is unable to establish.

Profiles on the Holocene beaches (located on low platforms) (P13 and P14) are eutrophic and nutrient-rich (Table III, Fig. 5) and showed cryoturbation, despite the absence of permafrost during fieldwork. Marine terraces are uplifted about 20 m a.s.l from present beaches and experienced severe reworking where vegetation is scarce. Soils are deep, with horizon development and differentiation, gradual transition, and coarse texture with a great amount of gravel at the surface (Table II). The pH varied from alkaline to slightly acid reflect diverse parent material and age of exposure. The P content was high, notably at P14, affected by fauna influence. Also, amounts of K^+, Na^+, and Ca^{2+} were high, mainly at the surface, while Mg^{2+} content was moderate (Table III). Base saturation was high, but P14 was classified as dystric; despite its proximity to the sea, both profiles had Na^+ with only 6 % of the cation exchange complex. The OM was greater in soil P13, reaching 3 % at the B horizon, and soil P14 presented only 0.5 % at the same depth. Micronutrients levels were high, particularly Fe.

The vegetation cover was discontinuous in both profiles. P13 showed a dominance of the phanerogam *C. quitensis* associated with mosses *S. uncinata* and *Polytrichastrum alpinum* less frequent, with the presence of roots in horizon A. The main cover of P14 was the grass *D. antarctica*, with roots present in the A horizon. The orange-colored crustose lichen *Caloplaca regalis* was frequent on exposed rocks.

DISCUSSION

Previous studies show that Elephant Island has an evident landform gradient (López-Martínez et al. 2012), soil types (Navas et al. 2018), vegetation establishment (Pereira & Putzke 1994, Schmitz et al. 2020a), and glacier retreat (Navas et al. 2018). Furthermore, Stinker Point is strongly influenced by the intense activity of seabirds (Petry et al. 2018) and a milder climate compared to continental Antarctica and other islands in the Antarctic Peninsula region. Our results present elements for understanding weathering, soil formation, and vegetation establishment in an isolated Maritime Antarctic spot. In addition, the local rocks are more resistant, and marine animals occupy extensive ice-free areas recently exposed.

Despite the milder climate, permafrost is found above 50 m a.s.l., mostly continuous under till and glacial deposits, and discontinuous on platforms, as confirmed observations by Navas et al. (2018). Clasts mantles of gravel and platy boulders are widespread and connect the upper platforms with the till accumulations, or the Holocene beaches. Despite the coarse texture of soils, water is abundant, and freezing-thawing cycles allow cryoclasty and movement of pebbles and blocks, frequently resting in planar positions (Simas et al. 2008, Chaves et al. 2017). Frost weathering is responsible for most of the physical break-up of the resistant metamorphic rocks accounting for the large quantity of coarse material at the surface (O'Brien et al. 1979). According to Navas et al. (2018), the bedding plans of these metamorphic rocks play an important role in physical weathering. On the other hand, the availability of liquid water and large breeding colonies favors chemical weathering (Michel et al. 2006, Simas et al. 2007, Siqueira et al. 2021). For example, these processes promote bases leaching, Fe availability, clay formation, and low pH in many soils, especially on platforms (MPS) and present-Holocene beaches (PHB) (Simas et al. 2008, Almeida et al. 2021). Hence, the rock constitution and sub-horizontal schistosity and bedding of regional outcrops are key for differences in weathering intensity found in Elephant Island, although both physical and chemical weathering is quite limited, resulting in shallow soils (Navas et al. 2018). Compared with other South Shetlands soils with rocks of volcanic origin, such as andesites and basalt mostly (e.g. Rei George, Nelson, Livingston, and Barrientos) (Navas et al. 2008, Francelino et al. 2011, Moura et al. 2012, Michel et al. 2014, Lopes et al. 2019, Daher et al. 2019, Rodrigues et al. 2019, Almeida et al. 2021) the soil development is less pronounced, due to the metamorphic nature of parent material, with much greater weathering resistance.

Most soils studied are located on the middle platforms, representing more stable surfaces exposed for a long time. On platforms, stable soils are suitable places for the occurrence of periglacial processes linked with active layers and snow patches (Navas et al. 2018). The most common periglacial features are stone fields, due to the abundance of coarse material (López-Martínez et al. 2012, 2016). There are significant differences in gravel contents when comparing TGD and PHB soils, suggesting differences in periglacial processes between landforms. In this sector, soils with the greatest ornithogenic influence are also found, with the typical higher P concentration. Because these areas were colonized by penguins, in the past, and at present, extending to adjacent sites, that are only indirectly influenced (Michel et al. 2006, Simas et al. 2007, Rodrigues et al. 2021). Similarly, higher soil organic matter on platforms is related to both biogenic activity and longer exposure time, with the presence of seabirds, responsible for soil nutrient input (Beyer et al. 2000, Bockheim & Haus 2014), and vegetation development (Schmitz et al. 2020b, Ferrari et al. 2021). The local vegetation is diverse and vigorous on the platforms of Stinker Point (Abakumov et al. 2017), with extensive moss carpets associated with fruticose and musciculous lichens, despite the common vertical stone fields at the surface. On the wind protected faces, where little snow accumulation takes place, crustose lichens develop. The highest species richness described for Stinker Point occurs on the platforms, where the native phanerogam specie *D. antarctica* is also found (Pereira & Putzke 1994, Schmitz et al. 2020a).

Table III. Chemical properties of the 20 soil profiles sampled in Stinker Point.

Horizon	Depth (cm)	pH		P	K	Na	Ca	Mg	Al	H+Al	BS	CECeff	CECT	PSB	Al sat	OM	P-Rem	Cu	Mn	Fe	Zn	N
		H_2O	KCl	---------- mg/dm^3---------			-------------------------$cmol_c/dm^3$--------------------------							%		dag/kg	mg/L	------------mg/dm^3--------------				dag/kg
Till/glacial deposit (TGD)																						
P1 – Turbic Leptic Skeletic Cryosol (Dystric, Ornithic)																						
A	5-15	4.84	4.5	279.2	166	146.2	1.41	1.54	0.2	7.8	4.01	4.21	11.81	34	4.8	3	44.6	1.12	2.1	112.6	1.82	0.21
B	15-35+	4.64	4.19	374.3	152	315.3	3.13	2.23	1.9	17.2	7.12	9.02	24.32	29.3	21.1	1.3	12.4	5.22	5.8	318.3	1.87	0.14
P2 – Turbic Cryosol (Dystric, Ornithic)																						
A	5-10	5	4.09	325	115	285.4	3.69	2.05	1.3	14.7	7.28	8.58	21.98	33.1	15.2	1.43	11.3	6.08	5	437.6	0.7	0.32
B1	10-22	4.77	2.96	287	91	155.2	2.11	2.49	7.4	21.3	5.51	12.91	26.81	20.6	57.3	0.52	19.3	4.83	6.4	460.3	0.79	0.15
B2	22-35	4.54	2.09	445.1	82	173.1	1.84	1.81	7.7	21.9	4.61	12.31	26.51	17.4	62.6	1.04	19.2	4.64	3.4	467.4	1.06	0.12
C	35-48	3.75	2.91	562.5	76	144.2	0.96	0.39	4.4	27.1	2.17	6.57	29.27	7.4	67	0.78	17.9	4.29	0.8	425.9	1.08	0.14
P10 - Turbic Cryosol ("Patterned", Eutric)																						
C1	0-25	7.83	7.78	168.1	231	27.4	3.69	0.36	0	0.3	4.76	4.76	5.06	94.1	0	0.9	37.4	11.91	57.6	1140.2	5.96	0.25
C2	25-50	7.96	7.6	200	155	18.5	3.64	0.3	0	1.5	4.42	4.42	5.92	74.7	0	1.29	40.2	17.03	39.7	899.5	4.8	0.14
C3	50-65+	7.91	7.82	225.3	181	20.5	4.53	0.38	0	0.3	5.46	5.46	5.76	94.8	0	1.03	43.1	19.45	51.6	1251.8	5.81	0.23
P11 - Turbic Leptic Cryosol ("Patterned", Eutric)																						
C1	0-10	7.69	7.6	123	116	31.4	2.62	0.23	0	0.2	3.28	3.28	3.48	94.3	0	1.42	37.6	13.39	53.6	1036.3	5.81	0.08
C2	10-20	7.98	7.82	135.5	181	37.4	4.35	0.37	0	0.2	5.35	5.35	5.55	96.4	0	1.55	28.4	9.84	41	710.3	4.32	0.12
C3	20-35+	7.85	7.01	195.6	127	32.4	3.64	0.55	0	0.2	4.66	4.66	4.86	95.9	0	1.16	42.9	8.87	36.1	480.7	3.28	0.14
P12 - Turbic Leptic Cryosol ("Patterned", Eutric)																						
C1	0-12	7.9	7.58	280.6	154	32.4	4.03	0.48	0	0.3	5.05	5.05	5.35	94.4	0	1.68	32.9	13.92	46.8	725.1	5.85	0.04
C2	12-40	6.22	7.58	255.7	196	36.4	3.62	0.38	0	0.7	4.66	4.66	5.36	86.9	0	2.45	31.7	12.21	37.8	440.4	4.34	0.18
P17 – Turbic Leptic Cryosol ("Patterned", Eutric)																						
C1	0-12	7.73	6.98	183.9	173	56.3	4.82	0.45	0	0.5	5.96	5.96	6.46	92.3	0	0.13	37.4	13.25	46	985.7	6.2	0.21
C2	12-35+	7.93	7.47	186.8	191	52.3	5.17	0.39	0	0.8	6.28	6.28	7.08	88.7	0	0.39	33.6	14.69	58.6	1242.6	7.55	0.30
P18 - Turbic Cryosol ("Patterned", Eutric)																						
C1	0-10	7.84	7.72	163.8	171	59.3	4.49	0.54	0	0.3	5.73	5.73	6.03	95	0	1.81	36.3	13.86	51.1	1358.5	7.4	0.12
C2	10-22	7.91	7.85	172.6	176	42.4	5.07	0.58	0	0.8	6.29	6.29	7.09	88.7	0	0.9	33.7	9.66	34	721.6	4.42	0.10
C3	22-30	7.89	7.76	148.2	166	37.4	4.89	0.57	0	0.3	6.05	6.05	6.35	95.3	0	1.68	32.7	9.47	32.8	725.2	4.25	0.16

Table III. (continued)

Horizon	Depth (cm)	pH		P	K	Na	Ca	Mg	Al	H + Al	BS	CECeff	CECT	PSB	Al sat	OM	P-Rem	Cu	Mn	Fe	Zn	N
		H_2O	KCl	---------- mg/dm³---------			-------------------------cmol$_c$/dm³--------------------------							%		dag/kg	mg/L	------------mg/dm³--------------				dag/kg
Middle platforms and scarps (MPS)																						
P3 - Turbic Leptic Skeletic Cryosol (Dystric, Ornithic)																						
A	0-12	4.24	3.56	710	63	85.4	1.14	0.23	5.7	30.2	1.9	7.6	32.1	5.9	75	1.17	28.6	3.47	0.4	292.1	0.75	0.17
BC	12-40	4.17	3.22	1142.5	82	112.3	1.48	0.36	5.5	25.2	2.54	8.04	27.74	9.2	68.4	1.04	28.2	4.88	0.5	301.9	0.97	0.22
P4 – Turbic Leptic Skeletic Cryosol (Dystric, Arenic, Ornithic)																						
A/O	3-6	4.25	3.84	560.6	76	89.4	0.68	0.26	4.4	21.6	1.52	5.92	23.12	6.6	74.3	2.48	24.6	8.06	1.8	902.2	1.81	0.14
A	6-10	4.14	4.13	787.4	79	167.1	1.24	0.38	3.1	17.7	2.55	5.65	20.25	12.6	54.9	1.43	13	6.69	1.4	563.6	2.18	0.15
BR	10-35+	4.14	3.6	622.7	91	90.4	0.75	0.24	4.3	17.3	1.62	5.92	18.92	8.6	72.6	1.17	30.5	5.13	1.1	558.5	1.22	0.03
P5 - Turbic Leptic Cryosol (Dystric, Arenic)																						
A/O1	0-5	4.65	4.35	15.8	15	2.6	1.45	0.38	0.6	4.8	1.88	2.48	6.68	28.1	24.2	1.43	24.7	1.87	23.9	67.7	1.59	0.17
A/O2	5-10	4.82	3.95	21.7	41	0.6	0.68	0.27	1.1	4.5	1.06	2.16	5.56	19.1	50.9	1.43	34.3	0.88	7.2	135.2	0.87	0.22
B	10-30	4.66	5.28	3.9	58	0	1.09	0.23	0.9	9.6	1.47	2.37	11.07	13.3	38	1.57	11	1.94	3.9	43.8	3.15	0.03
P7 - Turbic Leptic Skeletic Cryosol ("Patterned", Dystric, Ornithic)																						
A	0-10	5.35	4.82	5894	76	215.6	6.63	1.47	0	6.6	9.23	9.23	15.83	58.3	0	1.43	44.1	30.24	16.4	296.5	84.78	0.19
AB	10-17	5.54	5.56	5644.5	56	235.5	4.55	0.73	0	4	6.45	6.45	10.45	61.7	0	1.3	42.5	43.62	13.1	327.6	90.3	0.32
B	17-40	5.3	4.06	1217.1	55	55.5	2.83	0.36	0.5	4.5	3.57	4.07	8.07	44.2	12.3	1.43	47.5	9.53	1.6	169.5	6.37	0.21
P8 - Turbic Leptic Skeletic Cryosol ("Patterned", Dystric, Ornithic)																						
O	0-5	4.81	4.27	4547.2	48	181.1	5.15	1.37	0.3	10.4	7.43	7.73	17.83	41.7	3.9	10.1	38.9	12.73	8.4	175.2	63.4	0.19
A	5-10	5.24	4.5	6761.8	38	192.1	4.49	0.83	0	7.1	6.25	6.25	13.35	46.8	0	2.61	46.3	22.91	11.6	364.9	81.1	0.38
BR	10-30	5.16	3.7	880.2	65	71.4	3.03	0.28	0.5	5.6	3.79	4.29	9.39	40.4	11.7	1.3	48.2	5.47	0.9	144.2	3.2	0.29
P9 - Turbic Leptic Skeletic Cryosol ("Patterned", Eutric, Ornithic)																						
A	0-15	4.64	4.08	1019.9	76	108.3	3.82	1.38	0.5	8.1	5.87	6.37	13.97	42	7.8	2.61	38.6	7.06	6.2	165.2	8.16	0.21
B	15-30	5.21	5.02	6880.9	35	175.7	8.19	1.29	0	8.6	10.33	10.33	18.93	54.6	0	4.17	32.9	42.3	15	176	112.38	0.14
P15 – Turbic Leptic Skeletic Cryosol (Eutric, Ornithic)																						
A	0-12	5.69	5.34	5407.8	176	314.1	8.15	2.99	0	10.7	12.96	12.96	23.66	54.8	0	3.1	42.3	25.95	7	209.2	92.2	0.15
B	12-35+	5.33	4.35	7742.3	183	314.1	6.09	1.16	0	11.1	9.08	9.08	20.18	45	0	3.23	56.7	19.01	6.4	246.5	88.8	0.23

Table III. (continued)

Horizon	Depth (cm)	pH		P	K	Na	Ca	Mg	Al	H + Al	BS	CECeff	CEC T	PSB	Al sat	OM	P-Rem	Cu	Mn	Fe	Zn	N
		H_2O	KCl	----------- mg/dm³-- ------			--------------------------cmol$_c$/dm³--------------------- -----							%		dag/ kg	mg/L	------------mg/dm³--------------				dag/ kg
P16 – Turbic Leptic Skeletic Cryosol (Dystric, Ornithic)																						
A	0-5	4.97	4.32	154.6	87	87.2	1.32	0.65	0	5.4	2.57	2.57	7.97	32.2	0	6.46	56.1	0.99	1.1	108.3	2.12	0.25
C1	5-15	4.69	4.09	4805.8	131	294.2	5.01	0.82	0	9.2	7.45	7.45	16.65	44.7	0	4.13	47.5	30.05	8.4	305.6	99.7	0.22
C2	15-40+	4.6	3.62	3010.7	251	185.9	5.59	0.53	0.7	14.7	7.57	8.27	22.27	34	8.5	3.23	52.1	16.14	4	410.2	28.4	0.06
C2incl	25-35	4.37	3.37	5452.6	441	184.6	4.17	0.54	1.3	21.8	6.64	7.94	28.44	23.3	16.4	4	45.2	21.68	1.2	606.3	10.8	0.15
P19 - Turbic Leptic Skeletic Cryosol (Dystric, Arenic, Ornithic)																						
O/A	0-12	4.8	4.1	3362.88	157	324.1	4.72	1.54	0.1	10.7	8.07	8.17	18.77	43	1.2	10.9	58.6	14.71	5.4	287.8	40.8	0.03
B	12-20	5	4.42	7764.2	89	344	7.89	1.37	0.1	12.2	10.9	11.08	23.18	47.4	0.9	3.88	44.9	31.35	11	227.4	93.6	0.04
C	20-40	4.8	3.89	4117.5	166	324.1	6.4	0.89	0.1	12.4	9.12	9.22	21.52	42.4	1.1	3.1	52	17.73	8.2	287.1	61.1	0.37
P20 - Turbic Leptic Cryosol (Eutric, Arenic, Ornithic)																						
A	0-5	5.5	4.52	3667.8	36	152	3.12	1.06	0	5.3	4.93	4.93	10.23	48.2	0	0.52	42.8	15.87	24	799.5	38.6	0.07
B	5-15	5.81	4.37	1326.2	56	77.2	2.09	0.54	0	2.5	3.11	3.11	5.61	55.4	0	0.78	50.4	14.17	8.9	628.5	14.63	0.10
C	15-40+	6.34	5.02	655.5	59	42.4	2.24	0.49	0	1.8	3.07	3.07	4.87	63	0	1.03	54	19.89	11	628.4	6.68	0.06
Present-day/Holocene beaches																						
P6- Dystric Arenosol (Gelic)																						
1A	0-25	5.29	5.2	13.3	109	5.6	1.76	0.44	0	7.1	2.5	2.5	9.6	26	0	0.78	15.9	1.7	6.5	35.4	5.45	0.15
2B1	25-55	5.15	4.55	11.9	40	0	1.35	0.43	0	3.8	1.88	1.88	5.68	33.1	0	0.65	32.4	2.06	6.1	42.4	6.73	0.18
2B2	55-70+	4.9	3.74	1228.9	38	14.6	0.18	0.04	0.3	1.5	0.38	0.68	1.88	20.2	44.1	1.17	49.5	0.97	0.5	227.4	0.31	0.22
P13 - Eutric Regosol (Gelic, Ornithic, Turbic)																						
A	0-10	7.9	5.31	338.5	116	80.2	2.34	0.74	0	1.5	3.73	3.73	5.23	71.3	0	1.03	48.3	10.34	23.1	383.7	4.2	0.03
B	10-28	7.1	6.38	694.3	124	69.3	2.44	0.53	0	0.8	3.59	3.59	4.39	81.8	0	3.1	46.8	14.32	31.4	625.7	5.34	0.03
C1	28-45	7.15	6.56	361.8	112	54.3	2.68	0.39	0	0.8	3.59	3.59	4.39	81.8	0	1.42	51.8	13.21	30.4	667.7	4.8	0.08
C2	45-60+	7.26	4.48	383.8	115	44.4	3.15	0.33	0	0.7	3.97	3.97	4.67	85	0	1.68	49.5	10.22	24	427.3	3.51	0.05
P14 - Dystric Regosol (Gelic, Ornithic, Turbic)																						
A	0-10	5.43	4.5	1726.2	173	139	2.34	0.67	0	5.4	4.06	4.06	9.46	42.9	0	0.26	55.5	5.57	3.9	641.3	9.36	0.06
B	10-25	4.44	3.37	638.6	166	60.3	1.21	0.33	0.4	7.3	2.23	2.63	9.53	23.4	15.2	0.52	47.3	8.47	3.7	549.2	3.87	0.05
C1	25-45+	5.32	3.85	657.6	167	48.4	1.78	0.49	0.1	3.8	2.91	3.01	6.71	43.4	3.3	0.26	46.4	17.52	11.6	802	6.66	0.05
C	15-40+	6.34	5.02	655.5	59	42.4	2.24	0.49	0	1.8	3.07	3.07	4.87	63	0	1.03	54	19.89	11	628.4	6.68	0.06

Till and glacial deposits dominate the ice-free areas of Stinker Point (López-Martínez et al. 2012, Navas et al. 2018). Extensive areas of till dominate sections of modern deglaciation, at the study site, the ice has moved back further 200 m since it was drawing 1971 (Burley 1972, Navas et al. 2018). A large glacier surrounds Stinker Point, its front is a domain by dead ice and no paraglacial processes were identified. On the till deposits, periglacial features associated with active layer processes, frost heave, and ice segregation are common (gelifluction lobes, frost mounds, and patterned ground). In these recently exposed areas with continuous permafrost, the soils remain saturated, forming meltwater lakes, during the snowmelt period, and following the glacier retreat. These lakes are often used by skuas (Quintana & Travaini 2000), representing initial spots for plant colonization, and nutrient input in the soil (Otero et al. 2018, Schmitz et al. 2020a).

In soils at the present-day and Holocene beaches, permafrost was not detected. The P contents showed the present or past influence of the fauna (Michel et al. 2006, Simas et al. 2007). The vegetation is discontinuous, formed by communities dominated by phanerogamous plants, such as *D. antarctica* (as also found on Livingston Island beaches by Navas et al. (2008) and *C. quitensis* that have a positive relationship with ornithogenic soils and tend to grow primarily in nutrient-rich environments influenced by birds (Ferrari et al. 2021). Despite being an area of strong marine influence, Na^+ levels are low than other sheltered areas, which were also reported by Schmitz et al. (2020a) elsewhere on Stinker Point Holocene beaches.

CONCLUSION

Our study provides an updated description of the main patterns that determine the soil-landform-vegetation interplays at Stinker Point, Elephant Island, Antarctica, which are shallow and skeletic, and show an intimate interplay with landform configuration and biogenic activity. The age of soil formation is similar to other islands of the South Shetland archipelago; however, presumably, the resistant metamorphic parent material and bedding do not favor chemical and physical weathering. Our results highlight that the middle platforms soils were the oldest but shallow, with discontinuous permafrost, and mostly ornithogenic, which is directly associated with the vegetation cover. Thus, this study allows us to infer that the soils affected by current penguin activity, hinder the growth of vegetation due to excess trampling. However, soils with intermediary ornithogenic influence have discontinuous vegetation and few species, whereas aged soils on old, abandoned penguin rookeries showed great vegetation diversity and growth.

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Author contributions

CEGRS and RFMM designed the study. DS and RFMM carried out the fieldwork, execution of the research, interpreted the results and wrote the first version of the manuscript. JP, DS and FRF identified the plant species. RFMM collected and classified the soils. DS, PMV and FRF processed the data and helped in the writing discussion. CEGRS, JLM and MRF supervised the research, contribued to the discussion and to the text review.