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Soil-chronosequence and Quaternary landscape evolution at the marine terraces of Harmony Point, Nelson Island, Maritime Antarctica

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Abstract: This study characterized the physical, chemical, macro- and micromorphological soil properties from three successive marine terrace levels from Harmony Point (Nelson Island, Maritime Antarctica) in order to understand the pedological signatures of Quaternary coastal landscape evolution of Maritime Antarctica. Soils were sampled on the Late Holocene beach (current beach) and Mid Holocene marine terraces higher up, at 3, 8, and 12 m a.s.l. At the lower levels, the predominant soils were Gelorthents, whereas Haplogelepts dominate the higher terraces. Soil properties are mostly influenced by parent material and faunal activity, in which cryoclastic (thermal weathering) and phosphatization are the main soil-forming processes. Soils from the upper levels are more developed, deeper with reddish colors, granular structures and incipient formation B horizon. These horizonation features highlight that soils vary according with age of glacier-isostatic terrace uplift, representing a Quaternary soil chronosequence. All marine terrace levels are Ornithogenic soils, at varying degrees. However, the presence of old bird nesting sites for long periods led to formation of phosphatic horizons, stable Fe-phosphate minerals and abundant vegetation in the highest terraces of this part of Maritime Antarctica.

Key words: Antarctic soils, Holocene beaches, Ornithogenic soils, Soil mineralogy, Glacier-isostatic uplift.

INTRODUCTION

Maritime Antarctica (MA), the western coast of Antarctica Peninsula, South Sandwich and South Shetland Islands (SSI), are the main periglacial areas of Antarctica (Cannone & Guglielmin 2009, Campbell & Claridge 1987, López-Martínez et al. 2012). In MA, freeze-thawing processes are essential to understand the soil formation and long-term landscape evolution (French 1996). In addition, climate conditions of MA allow the proliferation of algae, lichens and extensive moss carpets (Campbell & Claridge 1987), enhancing the stability of underlying soils. Around 4-5 Ma ago, a long deglaciation period occurred and influenced the formation of the present-day landscapes (Björck et al. 1991, Björck & Zale 1996).

Several pedogeomorphological studies have been carried out in MA (e.g. Francelino et al. 2011, López-Martínez et al. 2012, Moura et al. 2012, Rodrigues et al. 2019), classifying the marine terraces as Holocene beaches, and representing one of the most relevant landforms of this region (López-Martínez et al. 2012).

Marine terraces are mainly originated by isostatic uplift, following glacier retraction (Araya & Hervé 1972, Pallàs et al. 1995, Serrano

2003, Fretwell et al. 2010, Francelino et al. 2011). This type of uplift is generally ~0.44 mm greater than the tectonic one (Pallàs et al. 1995). Additionally, Fretwell et al. (2010) suggest a mean rate of elevation of 2.80 mm/year for the most elevated beach levels of SSI. These results indicate great sea-level oscillations, which corroborates the former wide extension of ice caps, and widespread thawing processes in SSI during the Holocene, after the LGM (Pallàs et al. 1995, Hall & Perry 2004).

After exposure, and under the influence of environmental factors (e.g. biological activity), marine terraces are subjected to pedogenesis (Francelino et al. 2011). For example, buried cyanobacteria and mosses indicate solifluction and/or periglacial erosion processes; phosphatization processes in the nesting sites is clearly associated with long-term bird-activity (Myrcha et al. 1985, Tatur 1989, Myrcha & Tatur 1991, Pereira et al. 2013, Schaefer et al. 2004, Simas et al. 2007, Rodrigues et al. 2021).

Cambisols and Regosols are the main soil types (IUSS Working Group WRB 2015) on Antarctic marine terraces (Francelino et al. 2011), but the interplay between the soil forming-processes, topographic variation of marine terraces and age, is still known. In order to understand these relations, soils from different altitudes (3, 8 and 12 m) from Harmony Point (HP; Nelson Island, Maritime Antarctica) were sampled and analyzed according to their physical, chemical, mineralogical and micromorphological properties. The study area in Nelson island was uplifted about 14.5-16.0 m above sea level (a.s.l.) during Middle Holocene (Bentley et al. 2005, Fretwell et al. 2010), and represents a typical setting of glacier retreat marine terraces uplift in MA.

MATERIALS AND METHODS

Study area

Harmony Point (HP) covers an area of 4 km^2 (S62°18'; W59°12'), located in Nelson Island (part of SSI), in which 5 % (8 km^2) of its total area (165 km^2; Fig. 1) is composed of ice-free areas.

The local weather is influenced by successive cyclonic systems, which originate intense, relatively warm and wet winds and precipitation (Bintanja 1995). The maritime influence in the SSI is clear (Rakusa-Suszczewski 1993, Wen et al. 1994), with a climate classified as a Southern Polar Oceanic or Etf (according to Köppen's climatic classification). The predominant wind directions are northwest, west, north, and southeast (Bintanja 1995, Braun et al. 2001, Setzer & Hungria 1994). Northwest and west winds are warm and most frequent, reaching high speeds in the transition late Summer/early Spring (Rakusa-Suszczewski 1993). The mean annual temperature is -2.8 °C (Ferron et al. 2004).

HP is geologically part of a magmatic arc formed between the Upper Cretaceous to Early Quaternary (Birkenmajer 1982, Kraus 2005, Smellie et al. 1980). The predominant rocks are andesitic lavas, basalts and tuffs, of Mesozoic to Cenozoic age (Smellie et al. 1984). The HP coastal domain is composed of sedimentary rocks of andesitic nature, with coarse granulometry (pebbles to coarse sand), and subjected to recent glacial reworking (John & Sudgen 1971), with an influence of gabbro intrusions. Gentoo Penguins (*Pygoscelis papua*) and Giant Petrels (*Macronectes giganteus*) nesting sites are commonly found on beaches, terraces and outcrops.

The lower (first) marine terrace level (MT-1) is located at 3 m a.s.l., composed of medium to large pebbles, with the composition of the raised beach. The second level (MT-2) is located at 8 m a.s.l., with a mix of pebbles or with or

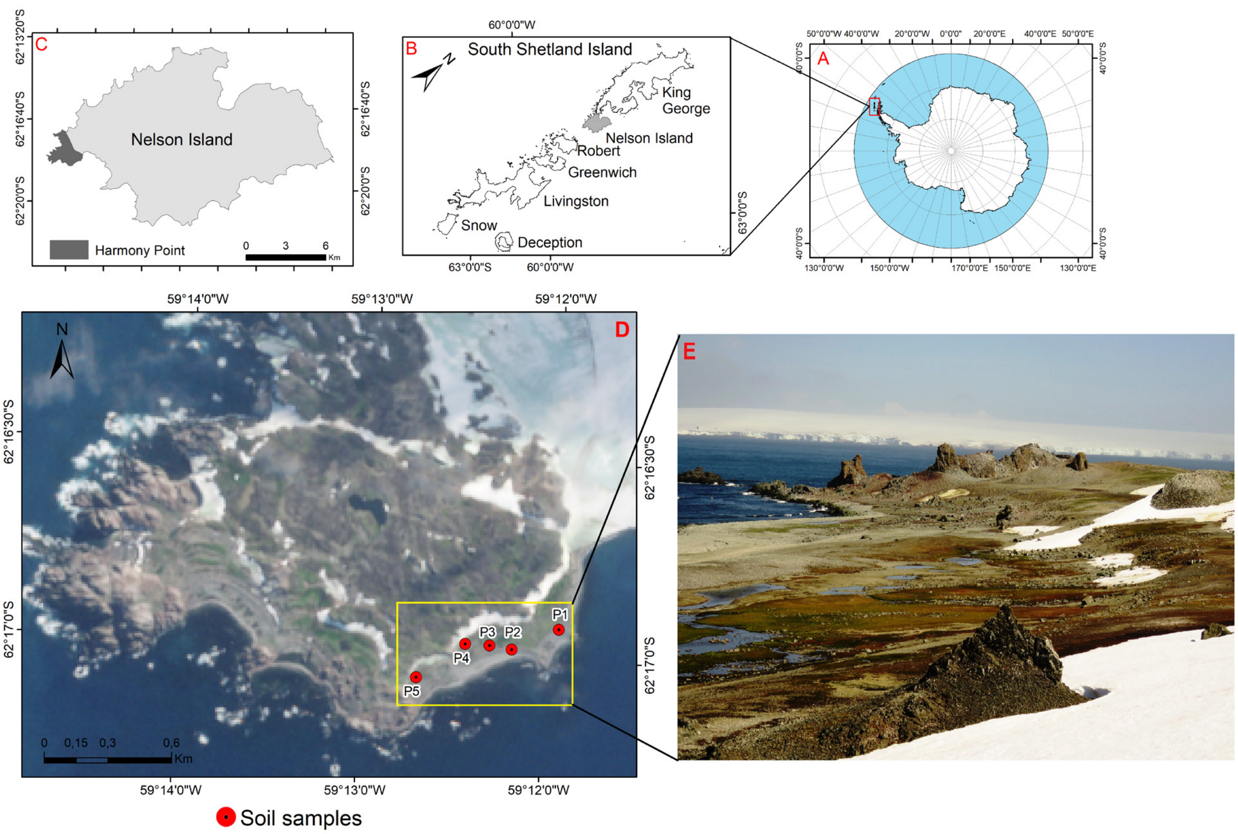

Figure 1. **Location of the studied area, Harmony Point, Nelson Island, Maritime Antarctica. A: Location of South Shetland Island in the Continent Antarctica. B: Location of South Shetland Islands. C: Nelson Island and Harmony Point location, D: Harmony Point area; E: Coastal domain location of the sampled soil profile.**

without lichens, but only incipiently vegetated, especially at the transition zone with MT-1. Also, flooding areas and ponds are covered by mosses carpet. The third level (MT-3) is located at 12 m a.s.l., under pebbly landsurfaces, and has more developed vegetation on lakes and melting channels, with mosses in the latter. Also, volcanic rock stacks occur occasionally, surrounded by debris slopes. Evidence of past nesting sites is clearly demonstrated by selective concentration of circular to ovoidal pebbly landforms on well-drained soils.

The vegetation from MA ice-free areas is predominantly cryptogamic (Olech 1993) and lichens, mosses and algae are among the autochthonous species (Victoria et al. 2009). Mosses are associated with flooded areas due to their good adaptation of waterlogging (Meick & Seppelt 1997, Schaefer et al. 2004). The marine terraces of HP, *Sanionia uncinata*, *Sanionia georgicouncinata*, *Brachythecium autrosalebrosu*, *Acarospora macrocyclus*,*Caloplaca* spp occur, whereas *Prasiola crispa* growth in places with intense bird's activity (Rodrigues et al. 2019).

Soil sampling and classification

Five pedons (P1, P2, P3, P4 and P5) were selected and dug to a depth of about 100 cm, with a total of 24 samples collected during the Summer of 2015. Sampling places were selected in order to assess a three level-sequence of uplifted marine terraces: P1 is related to the current beach (CB) and P2 to the first level (3 m; MT-1), P3 to the second level (8 m, MT-2) and P4 and P5 to the third level (12 m; MT-3; Fig. 2). All soil samples were air-dried before physical, chemical, mineralogical and micromorphological analyses were carried out in the laboratory (EMBRAPA 2017). Soils were pedologically described according to Schoeneberger et al. (2012) and classified according to Soil Taxonomy (Soil Survey Staff 2014) and WRB-FAO (IUSS Working Group WRB 2015).

Soil characterization

Soil texture was analyzed by mechanical dispersion of fine earth (< 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). All routine analytical chemical and physical determinations were obtained using standard procedures of EMBRAPA (2017). Soil pH (determined in 1:2.5 soil/water solution) and exchangeable nutrients were determined in < 2 mm air-dried samples (EMBRAPA 2017). Mg^{2+} and Al^{3+} were extracted with 1 mol/L KCl, and P, Na and K were extracted with Melich-1 (EMBRAPA 2017). Elemental concentrations in the extracts were determined by atomic absorption (Ca^{2+}, Mg^{2+} and Al^{3+}), flame emission (K and Na) and photocolorimetry (P) (Murphy & Riley 1962). Total organic carbon (TOC) was determined by wet oxidation, according to Yeomans & Bremer (1988).

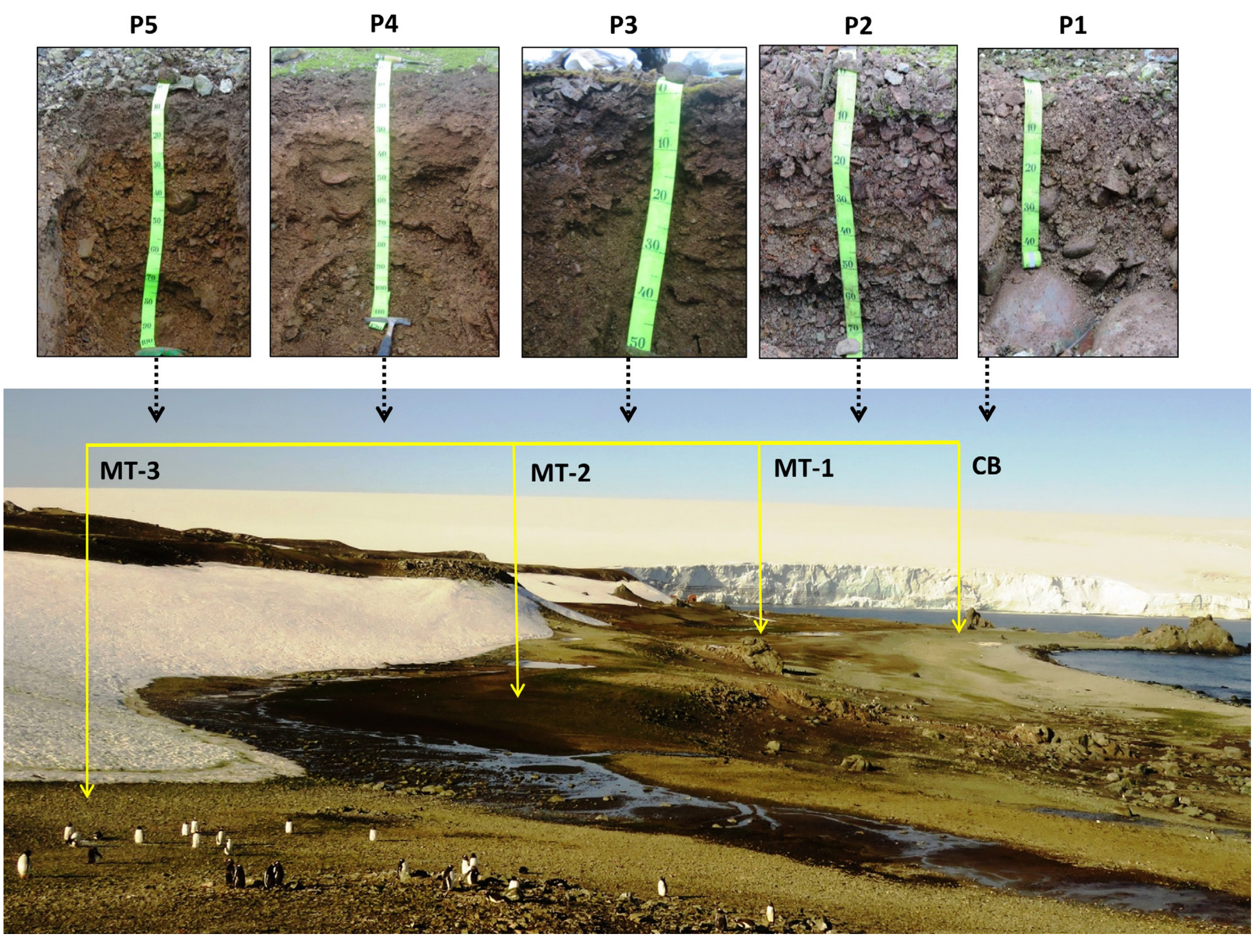

Figure 2. Coastal domain of HP and its respective levels of marine terraces and studied profiles. P1- current beach (CB); P2- marine terrace 1 (MT-1); P3- marine terrace 2 (MT-2); P4 and P5- marine terrace 3 (MT-3).

The mineralogical composition of the clay fraction of selected samples was studied by X-ray diffractometry (XRD). The clay was separated by centrifugation, and all analysis were carried out on natural clay. The diffractometer used is the Panalytical, Empyrean model, with CuKα radiation and power 45 kV and 40 mA. The scan interval was 2 to 70°, with a step of 0.02° 2θ and a count of 10 “/ step. The diffractograms were interpreted in X’Pert HighScore Plus software and through literature standards (Brindley and Brown 1980).

Secondary (pedogenic) Fe and Al oxides (Fe_{DCB} and Al_{DCB}) were extracted from the clay by dithionite-citrate-bicarbonate (McKeague & Day 1966). For the analysis of Fe and Al poorly crystalline forms (Fe_{OX} and Al_{OX}), 0.2 mol/L ammonium oxalate at pH 3.0 was used in the absence of light (Schwertmann 1973). Fe and Al (Fe_p and Al_p) bound to soil organic matter (OM) were extracted by sodium pyrophosphate according to proposed by Dahlgren (1994).

Undisturbed samples were impregnated with resin, and thin sections were produced, following the procedures of Filizola and Gomes (2004). The description was carried out with a Zeiss optical microscope, Axioskop model, using the terms proposed by Stoops (2003) and Stoops et al. (2010), with emphasis on cryogenic features (Schaefer et al. 2008).

Micromorphometrical analysis was performed using the free software *Jmicrovision©* 1.2.7. The geometry of particles was measured according to the following aspects: area, perimeter, length, width, and orientation (0º-180º). The rounding degree of 50 grains with granulometric values superior to sand (1-3 mm) was assessed, according to Cox (1927). In agreement with their orientations, grains were divided into three angular classes: 0º-44º/136º-180º, horizontal; 45º-74º/106º-135º, oblique; and 75º-105º, vertical. The software *Minitab®* 18.1 allowed originating the statistical and boxplot data. The tool *Magic Wand*, which is part of software *Jmicrovision©* 1.2.7, allowed obtaining the microporosity within thin sections.

Mean values for physical (i.e. roundness degree) and chemical properties (i.e. Fe_d and Al_d) were calculated with the aid of ANOVA and Tukey tests in order to determine and highlight the differences among the studied five pedons concerning their levels in the marine terraces. Non-parametric Kruskal-Wallis test (K-T) was performed for non-normally distributed data (i.e. soil properties). Differences were considered significant at $p < 0.05$. Principal Component Analysis (PCA) was used for correlated components. All statistical analyses were performed with the aid of Minitab® 18 software.

RESULTS

General characteristics of soil profiles

Morphological, physical (Table I and Fig. 2) and chemical (Table II) soil properties show the influence of parent material, topographic position, and biological activity.

At the current beach (CB) and first marine terrace level (MT-1), soils were classified as Typic Gelorthents (Soil Survey Staff 2014) or Haplic Arenosols (IUSS Working Group WRB 2015), respectively, with moderate to well-drainage conditions. Soil depth varies between 50-60 cm, and buried algae layers are observed in P2 (MT-1), leading to a horizon classification of 3Oib and 3Cb, were suffixes “i” and “b” stand for slightly decomposed organic matter, and for buried, respectively. These layers indicate the deposition of sediments and organic matter in different events at higher level, at the initial stages of isostatic compensation. On the surface, no vegetation occurs.

All horizons in P1 and surface horizons in P2 show dark grayish-brown to dark brown colors

Table I. Morphological and physical properties of soils from HP marine terraces.

Profile		Depth	Alt (m)	Geog. Coord.	Wet color	Structure	Trans.	Gravel > 2mm	Coarse sand	Fine sand	Silt	Clay	Textural Class	Soil Taxonomy	WRB/ FAO	Soil Taxonomy adapted
P1 - Current Beach (CB)																
A	0-12	3	S62°18.317' W059°11.593'	10YR 3/2	Md f gr	Clear wavy	10,4	72	4	7	17	Sandy loam	Typic Gelorthents	Haplic Arenosols	Ornithogenic Gelorthents	
C	12-40			10YR 4/3	Sg	Gradual wavy	10,8	67	5	10	18	Sandy loam				
2Cb	40-54			10YR 3/3	sg	-	10,4	62	6	13	18	Sandy loam				
P2 - Marine Terrace 1 (MT-1)																
A	1-25	6	S62°18.528' W059°12.198'	10YR 3/1	md f gr	Abrupt wavy	26,1	56	17	14	13	Sandy loam	Typic Gelorthents	Haplic Arenosols	Typic Gelorthents	
2C	25-45			2.5Y 4/2	sg	Abrupt wavy	9,1	80	3	8	10	Loamy sand				
3Oib	45-55			2.5YR3/2	-	Abrupt wavy	19,0	91	2	2	5	Sandy				
3Cb	55-65			2.5Y 4/2	sg	Abrupt wavy	26,4	71	8	10	11	Loamy sand				
P3 - Marine Terrace 2 (MT-2)																
O	0-3	15	S62°18.440' W059°11.810'	-			-		-	-	-	-	Typic Gelorthents	Haplic Arenosols	Ornithogenic Gelorthents	
A	03-8			5YR 3/2	Md f gr	Clear wavy	34,1	67	13	6	15	Sandy loam				
AC	8-18			10YR 3/4	sg	Clear wavy	66,8	84	3	3	10	Loamy sand				
2C1	18-50			10YR 4/4	sg	Clear wavy	72,5	86	2	2	9	Sandy				
P4 - Marine Terrace 3 (MT-3)																
O	0-2	23	S62°18.493' W059°12.267'		w m pl/ md m gr	-	21,3	54	20	14	12	Sandy loam	Typic Haplogelepts	Haplic Cambisols	Ornithogenic Haplogelepts	
A	2- 18			10YR 3/3	w m sb	Clear, wavy	53,3	51	17	17	16	Sandy loam				
B	18-26			7.5YR 4/2	md m bl	Clear wavy	26,8	54	12	17	17	Sandy loam				
Bw*	26-60			7.5YR 6/4	sg	Abrupt wavy	46,4	63	5	14	19	Sandy loam				
C1	60-80			10YR 3/6	sg	Clear wavy	25,0	89	0	2	9	Sandy				
C2	80-100			7.5YR 5/4	sg	Clear wavy	8,9	77	3	7	12	Sandy loam				
P5 - Marine Terrace 3 (MT-3)																
A	0-5	23	S62°18.587' W059°12.467'	10YR 3/1	md f gr	Abrupt wavy	7,3	30	35	22	13	Sandy loam	Typic Gelorthents	Haplic Arenosols	Ornithogenic Gelorthents	
AB	5- 15			10YR 4/2	W f pl	Abrupt wavy										
Bw	15-20			10YR 5/3	Md m sb	Abrupt wavy	26,8	35	9	35	22	Clay loam				
2C1	20-65			10YR 4/6	sg	Clear wavy										
C2	65-70			7.5YR5/6	sg		9,4	67	4	12	17	Sandy loam				

Development: w, weak; md, moderate; Size: f, fine; m, medium. Type: gr, granular; bl, subangular blocky; sg, single grain; * suffix w refers to the development of color and structure in the horizon (SSS, 2010). Trans.: Transition.

(10YR 3/2, 3/3), which is typical of soils derived of igneous rocks (Moura et al. 2012). Subsurface horizons in P2 have yellowish colors (2.5Y 4/2 to 2.5YR 3/2). Xanthic soils with similar chroma and hue can be likewise found within sulfide-rich rocks identified in Barton and Keller Peninsulas (Francelino et al. 2011, Lee et al. 2004, Lopes et al. 2017, Simas 2006). The sum of silt and clay particles is higher in P1 than P2, and the textural classes ranged from loamy sand to sandy loam. In addition, in both pedons, the main structure is single grain.

Chemical properties (Table II) show eutrophic soils in CB, and dystrophic soils in the MT-1. P1 shows the highest Na concentrations among all soils (1.56-1.87 $cmol_c/kg$), which can be explained by direct influence of sea spray. Soil pH values are low (3.90 to 5.10) in all soils. Exchangeable Ca^{2+} and Mg^{2+} concentrations are in the range of 1,39 to 10,3 $cmol_c/kg$ and 0,23 to 3.73 $cmol_c/kg$, respectively. The P-extractable concentrations are both high (P1 - 602 mg/kg; P2 - 365 mg/kg) due to the influence of penguin activity (Simas 2006).

P3 in the second marine terrace level (MT-2) has the same soil (CB as in MT-1), Typic Gelorthents (Soil Survey Staff, 2014) or Haplic Arenosols (IUSS Working Group WRB 2015). This soil has a depth of 75 cm, with similar morphological and physical properties with

Table II. Chemical properties of soils from HP marine terraces.

Horiz.	Depth	pH	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	BS	CEC_{eff}	CEC_{pot}	PBS	Al_{sat}	OM
		H_2O	KCl	-----mg/kg-----		-----------$cmol_c/kg$-----------								----%----		dag/kg
P1 - Current Beach (CB)																
A	0-12	4,2	3,5	597,1	0,67	1,87	2,86	3,73	1,3	8,7	9,1	10	18	51	12	1,37
C	12-40	4,7	3,4	307,6	0,64	1,82	1,74	2,9	1,3	6,3	7,1	8,4	13	53	15	1,43
2Cb	40-54	5,1	4	901,8	0,51	1,56	3,05	2,13	0,8	4,5	7,3	8	12	62	10	1,64
P2 - Marine Terrace 1 (MT-1)																
A	1-25	4,1	3,1	336,8	0,49	1,43	3,22	3,58	3,8	15,5	8,7	13	24	36	30	2,00
2C	25-45	4,5	3,1	296,4	0,45	0,91	1,45	1,3	3,2	8,4	4,1	7,3	13	33	44	1,38
3Oib	45-55	3,9	3,3	378,5	0,30	0,71	1,14	0,77	2,2	10,3	2,9	5,2	13	22	43	2,25
3Cb	55-65	4,3	3,2	446,5	0,46	0,87	1,97	1,8	3,2	8,8	5,1	8,3	14	37	39	1,88
P3 - Marine Terrace 2 (MT-2)																
O	0-3															
A	03-8	4,2	3,4	390,4	0,33	0,91	1,81	1,01	3	18,7	4,1	7,1	23	18	43	2,17
AC	8-18	4,4	3,3	640,5	0,34	0,91	1,67	0,77	5,2	19,5	3,7	8,9	23	16	58	3,73
2C1	18-50	4,7	3,3	928,1	0,30	0,71	1,82	0,67	3,8	8,4	3,5	7,3	12	29	52	4,67
P4 - Marine Terrace 3 (MT-3)																
O	0-2	4,6	4,2	3.514,50	0,80	1,39	10,2	3,23	0,1	9,5	16	16	25	62	1	1,96
A	2- 18	4,8	3,7	802	0,44	0,80	7,74	2,03	0,8	17,1	11	12	28	39	7	1,83
B	18-26	4	2,9	1.048,00	0,27	0,36	1,79	0,76	3,4	26,9	3,2	6,6	30	11	52	2,61
Bw	26-60	3,9	2,7	711,9	0,39	0,43	1,39	0,73	5,2	25,8	2,9	8,1	29	10	64	1,04
C1	60-80	4	2,8	1.184,10	0,23	0,30	1,18	0,67	5,5	16,4	2,4	7,9	19	13	70	1,04
C2	80-100	3,8	2,8	818,9	0,22	0,30	1,04	0,49	5	23,2	2	7	25	8	71	0,52
P5 - Marine Terrace 3 (MT-3)																
A	0-5	4,6	4,1	2.768,00	0,69	1,43	10,3	3,24	0	16,3	16	16	32	49	0	2,87
AB	05-15															
Bw	15-20	3,6	2,7	2.742,30	0,40	0,55	1,55	0,26	4	34,1	2,8	6,8	37	8	59	2,74
2C1	20-65															
C2	65-70	3,4	2,6	2.216,00	0,45	0,55	1,39	0,23	4,1	40,4	2,6	6,7	43	6	61	2,35

BS: sum of bases; CEC_{eff}: effective cation exchange capacity; CEC_{pot}: potential CEC at pH 7.0; PSB: percentage of bases saturation; Al_{sat}: Al saturation; OM: organic matter.

MT-3 (Table I), notably soil color and the granular to blocky structures in the surface horizons. Petrels nesting sites and an abundant vegetation cover of *Sanionia uncinata* can be observed at this terrace level, representing the dominant moss species in coastal areas of MA (Victoria et al. 2009). In all horizons of P3, pH is acid (3.9-4.5) and exchangeable Ca^{2+}, Mg^{2+} and K^{+} concentrations are the lowest (Table II). On the other hand, P content, exchangeable Al^{3+} and H+Al concentrations are higher than those obtained at the MT-1. Organic matter (OM) is also higher than P1, and its contents increases with depth.

The third level (MT-3) have Typic Haplogelepts/Haplic Cambisols (P4), and Typic Gelorthent/Haplic Arenosols (P5), by Soil Survey Staff (2014) and IUSS Working Group WRB (2015) classifications, respectively. Soils at the high terrace level are deeper (75-100 cm), and have B horizons and phosphate-rich layers. Surface horizons have brown (7.7YR 3/4) to dark brown (10YR 3/3) colors, due to organic matter incorporation, and B horizons are more palid (7.5YR 6/4; Table I) due to phosphate accumulation (Myrcha et al. 1983, Simas 2006, Simas et al. 2007, Tatur & Barczuk 1985). Values of pH and exchangeable cations at subsurface horizons in P4 and P5 were lower than those from the lower MT-1 and MT-2 levels (Table II). On the other hand, P-extractable (802-3,514.50 mg/dm^3) and exchangeable K^{+} and Al^{3+} concentrations are much higher than those of MT-1 and MT-2. CEC obtained values were high (i.e. HP-3 with 32-43 cmol$_c$/dm^3), and organic matter concentrations in A horizon are abundant due to the presence of vegetation cover of *Prasiola crispa* and *Sanionia uncinata*.

Mineralogy

Primary mineralogical assemblage of clay fraction of all sampled soils is composed of plagioclases ($NaAlSi_3O_8$-$CaAl_2Si_2O_8$), pyroxenes and quartz (SiO_2; Table III). According to XRD analysis, plagioclases are mostly andesine (3.21 Å) and anorthite (3.10 Å). The primary mineralogy of the clay fractions is very common in Antarctica soils due to physical weathering caused by cryoclasty and glacial erosion processes (Jeong et al. 2004, Michel et al. 2006, Schaefer et al. 2008, 2015, Simas 2006, Simas et al. 2008).

Other minerals in the clay fraction are illite {$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$; 10.60 Å}, smectite (15.10 Å), chlorite (14.19 Å), kaolinite [7.15 Å; $Al_2(OH)_4Si_2O_5$] and phosphates (Fig. 3). Chlorites are essentially authigenic in Antarctica's soils and may result from hydrothermal alteration of pyroxenes (Blume et al. 2004, Srivastava et al. 2011). On the other hand, smectites are formed by chemical weathering processes (Bockheim 1980, Borchardt 1989, Boyer 1975, Campbell & Claridge 1987, Gibson et al. 1983, Hillenbrand & Ehrmann 2001, Vennum & Nejedly 1990).

The mineral assemblage kaolinite+chlorite was identified in P1 and P2 pedons, as indicated by the peaks close to 7.15 Å, which disappear after being heated at 550 °C (Fig. 3). Kaolinite occurs in soils of MA (Blume et al. 2002, Schaefer et al. 2008, Simas et al. 2008) and its presence is explained by stronger chemical weathering in acid-sulfate soils, or weathering under cold, wet climates (Srivastava et al. 2011).

Phosphate minerals, such as struvite [$NH_4MgPO_4{\cdot}6H_2O$] and vivianite [$Fe^{2+}_3(PO_4)_2{\cdot}8H_2O$] were identified in the soils influenced by bird activities, being the predominant phases in MT-2 and MT-3 levels. Leucophosphite [$KFe^{3+}_2(PO_4)_2(OH){\cdot}2H_2O$] peaks are more intense in the Bw horizon of P5, higher up (Fig. 4). According to Tatur (1989), these minerals result of percolation of guano-rich solutions and the consequent reaction of the latter with primary minerals, such as plagioclases and pyroxenes.

Table III. Mineralogy of clay fraction and Fe and Al (%) concentrations extracted by dithionite-citrate-bicarbonate, ammonium oxalate and pyrophosphate methods from the HP soils of marine terraces.

Pedon	Clay fraction DRX	DBC		Oxalate		Pyrophosphate		Fe_{OX}/Fe_{DCB}	Al_{OX}/Al_{DCB}
		Fe_{DCB}	Al_{DCB}	Fe_{OX}	Al_{OX}	Fe_P	Al_P		
P1 - Current BeaChl (CB)									
A	Qz, Chl, Sm, Ko, An	2,1	0,49	2,82	0,59	0,28	0,15	1,34	1,2
C	Qz, Sm, An, Ko	4,24	0,59	4,98	0,76	0,14	0,1	1,17	1,29
2Cb	Qz, An, Chl, Ko, Vm	4,15	1,03	5,48	1,63	0,18	0,21	1,32	1,58
P2 - Marine Terrace 1 (MT-1)									
A	And, Chl, Sm	3,12	0,83	3,58	0,75	0,49	0,14	1,15	0,9
2C	And, Chl, Sm	7,57	0,73	8,32	0,79	0,31	0,08	1,1	1,08
3Oib	Qz,Chl, Sm,	5,41	0,67	6,19	0,8	0,25	0,08	1,14	1,19
3Cb	Chl, And, Chl, Sm	7,76	0,97	4,05	0,88	0,13	0,05	0,52	0,91
P3 - Marine Terrace 2 (MT-2)									
A	Chl, Ab, Sm	3,96	1	5,61	1,25	0,68	0,23	1,42	1,25
AC	Chl, Sm, Str	7,77	1,21	12,04	1,61	0,85	0,24	1,55	1,33
C1	Chl, Ab, Sm, Str	10,52	1,15	14,21	1,7	0,61	0,2	1,35	1,48
A	Chl, Ab, Sm	3,96	1	5,61	1,25	0,68	0,23	1,42	1,25
P4 - Marine Terrace 3 (MT-3)									
O	And, Sm, Le	7,7	1,77	9,91	2,07	0,91	0,58	1,29	1,17
A	Chl, And, Mt, Sm, Le	9,3	1,83	9,41	1,77	1,5	0,52	1,01	0,97
B	Qz, And, Chl, Sm, Le	12,98	2,73	10,19	1,87	1,2	0,41	0,79	0,68
Bw	Qz, Chl, Mt, Le, Str	11,69	1,88	25,19	2,95	0,57	0,24	2,15	1,57
C1	Chl, Mt, Le, Str, Vv	11,13	2,2	17,01	2,69	1,27	0,52	1,53	1,22
P5 - Marine Terrace 3 (MT-3)									
A	Qz, And, Sm, Le, Vv	4,56	1,49	6,98	2,24	0,65	0,55	1,53	1,5
Bw	Qz, And, Sm, Le, Vv	10,33	1,7	12,06	2,16	2,18	0,79	1,17	1,27
C2	And, Sm, Le	13,17	2,21	14,96	2,71	2,18	0,87	1,14	1,23

An: anatase; And: andesine; Chl: Chlorite; Ko: Kaolinite; Le: leucophosphite; Qz: quartz; Sm: smectite; Str: struvite; Vv: vivianite.

Fe_{DBC} and Al_{DCB} concentrations increase from MT-1 to MT-2 (Table III). In MT-3 (P4 and P5), Fe_{DCB} concentrations (Fe_{DCB} P4 = 7.70 -11.13 %; P5 = 4.56-13.17 %) are higher than Al_{DCB} (Al_{DCB} P4 = 1.77-2.73 %; P5 = 1.49-2.21 %), which suggests high amounts of this element in the parent material (i.e. andesitic rocks), explaining the high amounts of Fe-phosphate minerals in these soils (i.e. vivianite). The average concentrations of Al_P are lower than Fe_P (Al_P = 0.32 and Fe_P = 0.79), which demonstrates high affinity between the Fe-oxides and the organic matter. High Fe_{OX}/Fe_{DCB} ratios (0.72-2.15) in the studied soils (Table III) indicate high abundance of Fe phases of low crystallinity. The ratios Al_{OX}/Al_{DCB} are between 0.98-1.50 (Table III), which also implies Al phases with low crystallinity.

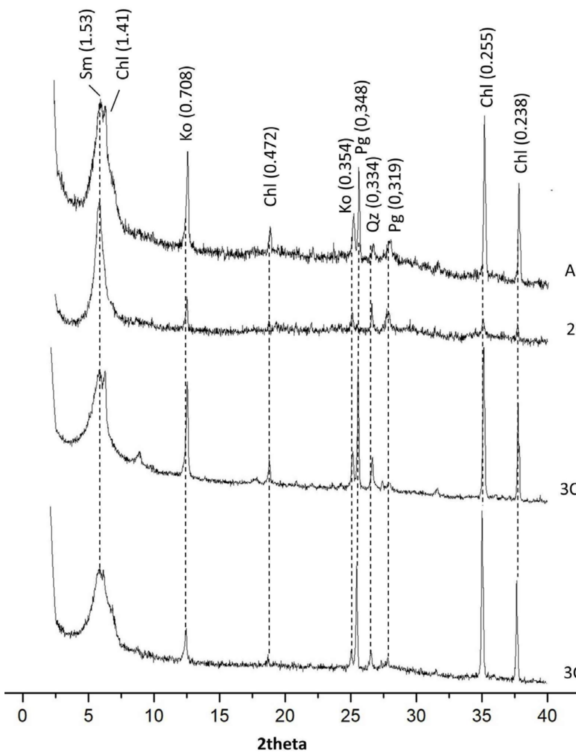

Figure 3. XRD spectrum of clay fraction within the pedon P2 (MT-1). Chl: chlorite, Sm: smectite, Ko: kaolinite Pg: plagioclase, Qz: quartz. "d" in nm.

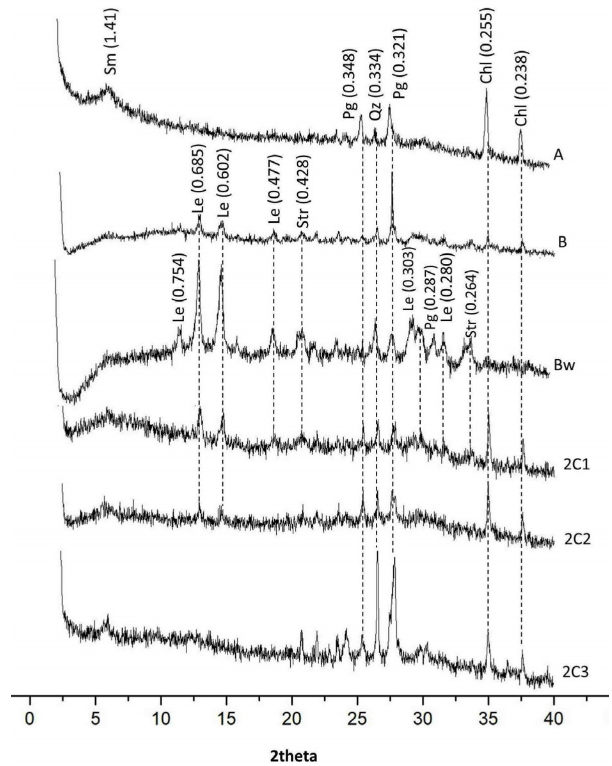

Figure 4. XRD spectrum of clay fraction within the pedon P4 (MT-3). Chl: chlorite, Sm: smectite, Pg: plagioclase, Qz: quartz, Le: Leucophosphite, Str: Struvite. "d" in nm.

Statistical data

Statistical results of soil properties from the analyzed pedons are shown in Table IV. ANOVA and Kruskal-Wallis tests were applied in order to distinguish soil proprieties among the pedons. ANOVA analyses show significant differences in H+Al (p = 0.006), CEC_{pot} (p = 0.000), OM (p = 0.007), Al_d (p = 0.001), Al_o (p = 0.001) and silt (p = 0.024) and clay fractions (p = 0.036). P4 and P5 yield the highest mean values of analyzed variables (i.e. OM) and are significantly different from P1, P2 and P3 (see Table IV). P3 exhibits the highest mean values of OM (3.50 dag/kg) and is significantly different from other pedons. Kruskal-Wallis tests also showed that P (p = 0.013), Na (p = 0.033), Fe_p (p = 0.009) and Al_p (p = 0.003) are significantly different. On the other hand, P2 show the lowest mean values of P (364,6 mg/kg), Fe_p (0,3 %) and Al_p (0,1 %).

The score plot for the first two principal components is showed in Fig. 5. PCA explained 70.90 % of total variance. First principal component is strongly correlated with Fe_{DCB}, Al^{3+}, Al_{sat} and Fe_{OX} scores (Supplementary Material - Table SI). On the other hand, second principal component is dominated by the negative loadings of silt and fine sand fractions and Al_p, Fe_p and Ca^{2+} scores (Table SI). PCA shows that pedons (P1, P2, P3, P4 and P5) can be divided into three groups (see ellipses in Fig. 5): surface horizons of P4 and P5; horizons of P1, P2 and P3; and subsurface horizons of P4 and P5.

Micromorphology and micromorphometry

The results of the micromorphological description are shown in Table V. Accompanying, photomicrographs of microstructures in thin

Table IV. Summary statistics of soil properties for pedons from HP marine terraces.

	Current Beach		MT-1		MT-2		MT-3				
Pedon	**P1**		**P2**		**P3**		**P4**		**P5**		**p-value**
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	
pH	4,6**a**	0,5	4,2**a**	0,3	4,4**a**	0,3	4,1**a**	0,4	3,8**a**	0,6	0,230
P* mg/kg	602,0	297,0	364,6	64,1	653,0	269,0	1347,0	1076,0	2575,0	312,0	**0,013**
K mg/kg	0,6**a**	0,1	0,4**a**	0,1	0,3**a**	0,0	0,4**a**	0,2	0,5**a**	0,2	0,212
Na* $cmol_c$/kg	1,8	0,2	1,0	0,3	0,8	0,1	0,6	0,4	0,8	0,5	**0,033**
Ca2+* $cmol_c$/kg	2,6	0,7	1,9	0,9	1,8	0,1	3,9	4,0	4,4	5,1	0,913
Mg2+* $cmol_c$/kg	2,9	0,8	1,9	1,2	0,8	0,2	1,3	1,1	1,2	1,7	0,180
Al3+ $cmol_c$/kg	1,1**a**	0,3	3,1**a**	0,7	4,0**a**	1,1	3,3**a**	2,4	2,7**a**	2,3	0,363
H + Al $cmol_c$/kg	6,5**b**	2,1	10,75**b**	3,3	15,53**ab**	6,2	19,82**ab**	6,7	30,27**a**	12,5	**0,006**
BS* $cmol_c$/kg	7,8	1,1	5,2	2,5	3,8	0,3	6,3	5,9	7,1	7,7	0,635
CECeff* $cmol_c$/kg	8,8	1,1	8,5	3,3	7,8	1,0	9,6	3,7	9,8	5,3	0,908
CECpot $cmol_c$/kg	14,33**c**	3,2	16**c**	5,4	19,3**bc**	6,4	26,0**b**	4,0	37,33**a**	5,5	**0,000**
PBS %	55,3 **a**	5,9	32,0 **a**	6,9	21,0 **a**	7,0	23,8 **a**	22,0	21,0 **a**	24,3	0,101
Al_{sat} %	12,3 **a**	2,5	39,0 **a**	6,4	51,0 **a**	7,6	44,2 **a**	31,9	40,0 **a**	34,7	0,342
OM dag/kg	1,5**b**	0,1	1,9**ab**	0,4	3,5**a**	1,3	1,5**b**	0,8	2,7**ab**	0,3	**0,007**
Fe_{DCB} %	3,5 **a**	1,2	6,0 **a**	2,2	7,4 **a**	3,3	9,5 **a**	3,3	9,4 **a**	4,4	0,097
Al_{DCB} %	0,7**b**	0,3	0,8**b**	0,1	1,1a**b**	0,1	1,9**a**	0,6	1,8**a**	0,4	**0,001**
Fe_{OX} %	4,4**a**	1,4	5,5**a**	2,2	10,6**a**	4,5	12,9**a**	7,1	11,3**a**	4,0	0,111
Al_{OX} %	1,0**b**	0,6	0,8**b**	0,1	1,5**ab**	0,2	2,1**a**	0,6	2,4**a**	0,3	**0,001**
Fe_P* %	0,2	0,1	0,3	0,2	0,7	0,1	1,0	0,4	1,7	0,9	**0,009**
Al_P* %	0,2	0,1	0,1	0,0	0,2	0,0	0,4	0,2	0,7	0,2	**0,003**
Fe_{OX}/Fe_{DCB}*	1,3**a**	0,1	1,0**a**	0,3	1,4**a**	0,1	1,4**a**	0,5	1,3**a**	0,2	0,390
Al_{OX}/Al_{DCB}*	1,4**a**	0,2	1,0**a**	0,1	1,4**a**	0,1	1,1**a**	0,3	1,3**a**	0,1	0,180
Gravel* %	10,5	0,2	20,2	8,1	57,8	20,7	30,3	16,5	14,5	10,7	0,072
Coarse sand %	67,0**a**	5,0	74,5**a**	14,8	79,0**a**	10,4	64,7**a**	15,2	44,0**a**	20,1	0,071
Fine sand* %	5,0	1,0	7,5	6,9	6,0	6,1	9,5	8,1	16,0	16,6	0,773
Silt %	10,0**ab**	3,0	8,5**ab**	5,0	3,7**b**	2,1	11,8**ab**	6,1	23,0**a**	11,5	**0,024**
Clay %	17,7**a**	0,6	9,8**a**	3,4	11,3**a**	3,2	14,2**a**	3,8	17,3**a**	4,5	**0,036**

*** indicates that variables were analyzed by Kruskal–Wallis (K-T) test. The other variables were analyzed by ANOVA followed by a Tukey test. Means that do not share a letter are significantly different, the other indicated by the same letter are not significantly different. Bolder numbers in p-value indicate that is significantly different. MT: marine terrace. [a]Percent of particles > 2 mm.**

sections are illustrated in Fig. 6, whereas Fig. 7 and 8 show the pore size boxplot and Cox rounding index, respectively.

Soils from MT-1 show simple packing voids (Fig. 6). Pores occupy 40 % of thin section area and their average size is 0.30 mm (Fig. 7). Pores surfaces are generally smooth and regular, though some of them show rough boundaries. Lithic fragments show zigzag-like planes, well fit, regular and smooth, which may have resulted from cryoclastic processes (Van Vliet-Lanoe 1985). Due to the lack of aggregates, microstructures are associated to Monic Basic-related distribution pattern and are mainly composed of coarse grains, such as sand grains and pebbles. These grains are andesite

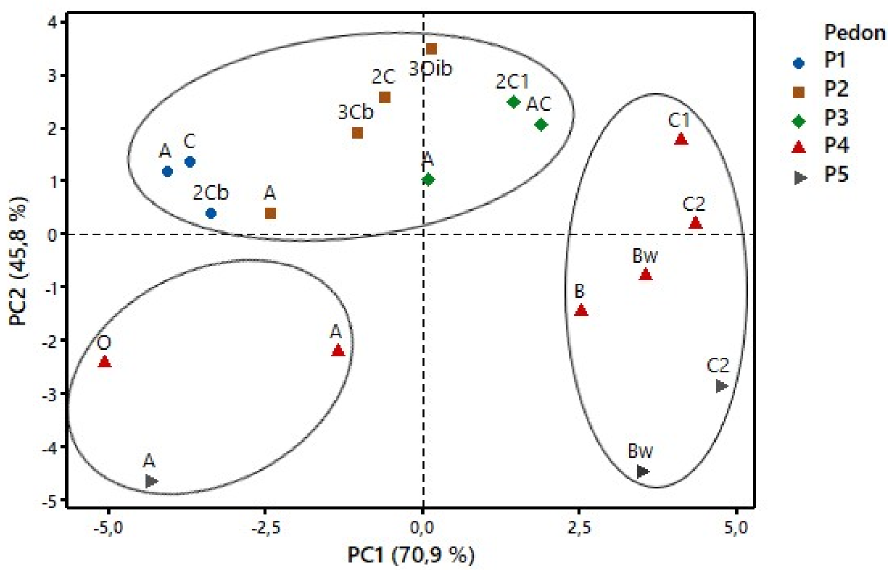

Figure 5. **Principal component analysis (PCA) of the soil variables analysed. Three groups of correlated variables and three groups of samples associated with them (indicated by ellipses).**

rock fragments, whose predominant mineral assemblage is formed by opaque minerals (pyrite), plagioclases and pyroxenes.

MT-1 soils have an average size of the grains of 0.60 mm, and are predominantly angular. The grain roundness is lower than those in MT-2 and MT-3 levels (Fig. 8). Orientation-related data show 62 % horizontal, 26 % vertical and 12 % oblique grains. Fine materials occur within lithic fragments (as infillings) and also as grains resulting from the alteration of mafic minerals, with brown to yellowish colors and a crystallitic b-fabric. In addition, few residues of *Prasiola crispa* with low decomposition degree can be observed.

Soils from MT-2 show simple packing voids (Fig. 6) and are composed of lithic fragments of pebble granulometry, which are filled with sand-sized fragments. These fragments occupy 25 % of thin section area and show an average size of 0.14 mm. Large grains are coated by a clay micromass that form a basic chitonic microstructure (Stoops 2003).

Among the lithic fragments, volcanic andesites are predominant, which is typical of marine terraces. 65 % of thin section area shows coated grains, with roundness indices of 0.76. The average size is 0.60 mm, and grains orientations were 57 % horizontal, 4 % vertical, and 39 % oblique. The relative distribution pattern was chitonic, with increasing density of the fine materials in places, originating a chito-gefuric related distribution pattern. The micromass shows a brown-reddish color, limpid aspect and undifferentiated b-fabric. The isotropic pattern associated to the limpid aspect suggests amorphous materials (Sedov et al. 2010). Organic tissues of *Sanionia uncinata* can be observed, with a more advanced decomposition stage; bone fragments are altered and oxidized. Illuvial coatings on coarse grains, and infillings are common pedofeatures.

The soils of MT-3 show planar voids, deformed vesicles and vughs, which occupy 16 % of the thin section, with mean pores size of 0.10 mm, smaller than MT-1 and MT-2 (Fig. 6).

Microstructure is small subangular blocky, formed by the coalescent arrangement of granular aggregates, and coarse sand grains, and the related distribution pattern is classified as enaulic. Coarse material arrangement observed in MT-3 is similar to MT-2, mainly lithic fragments of volcanic andesitic nature, comprising 35 % of the thin section area and average size of 0.60

Table V. Micromorphological properties of the soils from HP marine terraces.

Microestructure	Groundmass			Organic material	Pedofeautures
	Coarse Material	Fine Material	$C/F_{2\mu m}$ relative distribution		
P2 - Marine Terrace 1 (MT-1) - A horizon					
Single grain microstructure, with few fine, pore of simple-packing voids.	Cryoclast plutonic rock fragments (diabase) and fragments of opaque minerals (possibly pyrite), plagioclase and pyroxenes.	Yellowish brown color, limpid e crystallitic b-fabric.	Coarse monic.	Rare fragments of Prasiola crispa in low decomposition stage.	Not found.
P3 - Marine Terrace 2 (MT-2) - A horizon					
Chitonic (Pelicular grain microstructure), with thick material being coated by thin coating of fine, sinple packing voids.	Fragments of andesitic volcanic rock. It presents lithological heterogeneity of gravel and coarse sand.	Probable presence of amorphous, reddish brown color, limpid e undifferentiated b-fabric.	Chitonic and Chito-gefuric.	Fragments of *Sanionia uncinata* in intermediate stage of decomposition and fragments of oxidized bones.	Coating around the lithic fragments. It presents cracks that individualize the coating in several fragments.
P5 - Marine Terrace 3 (MT-3) - Bw horizon					
Subangular blocky microstructure, moderately separated, planes voids, deformed vesicles and vughs.	Fragments of andesitic volcanic rock. It presents lithological heterogeneity of gravel and coarse sand. . Calcite intrusions are present in some fragments.	Micromass 1 of the aggregates: yellowish brown color, speckled e crystallitic b-fabric. Micromass2: reddish brown, limpid e undifferentiated b-fabric.	Single-spaced equal enaulic.	Fragments of *Sanionia uncinata* in advanced stage of decomposition. Many fragments of bones.	Coating around the lithic fragments. Fissures that individualize the coating in various fragments.

mm. The average values obtained for the Cox (1927) index is 0.74, which is related to subangular grains; however, the variation amplitude of grains yields values close to 1.00 (Fig. 8).

In MT-3 the grains are oriented as follows: 46 % horizontal, 18 % vertical and 36 % oblique. Two distinct types of micromasses can be observed. The first originates aggregates composed of silt to fine sand particles and lithic fragments with granulometric size slightly more prominent than sand grains; it also shows brown-yellowish color, speckled aspect and crystallitic b-fabric. The second is very similar to micromass of MT-3, with coating of pebbles with a brown-reddish color, limpid aspect and undifferentiated b-fabric. Finally, the pedofeatures of MT-3 are clay coatings on coarse grains, and infillings.

DISCUSSION

Soil properties

The soils of HP marine terraces are similar to others from coastal areas of MA (Haus et al. 2016, Moura et al. 2012, Navas et al. 2006, 2008, Simas et al. 2007, Tatur 1989), showing a great pedogenic development with increasing altitude. These observations are corroborated

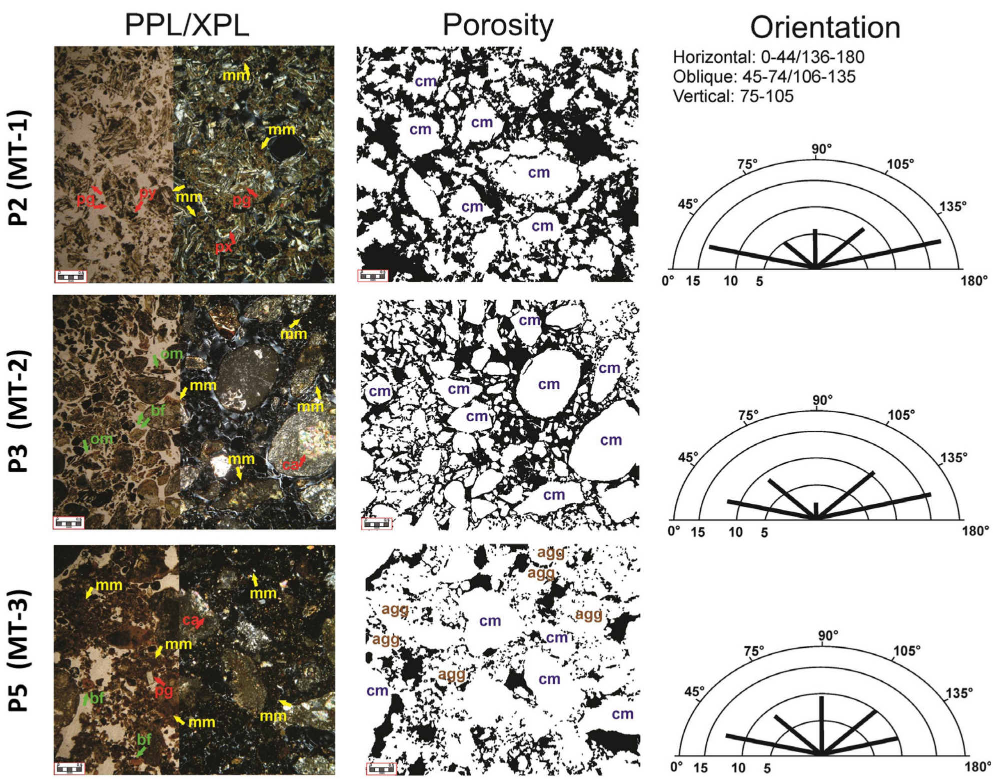

Figure 6. Photomicrographs of microstructures, in which appear the porosity extraction (black) and the orientation of the grains in the soils within the distinct levels of marine terraces.Py = pirita; Pg = plagioclase; Px = pyroxene; Ca = calcite; Bf = bone fragment; Om = organic matter; Mm = Micromass; Cm = coarse material; Agg = aggregate. Each semi-circle stands for isolines of grain amount. MT: marine terrace.

by physical, chemical, mineralogical and micromorphological soil properties.

Morphologically, the upper terrace soils (MT-2 and MT-3) exhibit more stable structures, are thicker, with higher chroma, displaying marked horizons. In the MT-3, the formation of Bw horizon (Schoeneberger et al. 2012) with cambic features, at 21 cm depth, reveals the greater pedogenetic evolution of old terraces. Haus et al. (2016) also reported Bw horizon formation at higher and older levels of marine terraces in the Peninsula.

All soils from HP marine terraces are skeletal (80 % V/V granulometric fractions > 2 mm diameter), and consistent with other studies in the SSI (Simas et al. 2007). However, lithic fragments at the upper terrace soils (P4 and P5) are smaller and more degraded than lower ones (P1, P2 and P3). This can be explained by the greater age of pebbles at MT-3 to physical weathering (Francelino et al. 2011, Michel et al. 2014, Rodrigues et al. 2019, Simas et al. 2008), resulting in breaking up into smaller fragments.

We observed an anomalous behavior of clay content along the soil sequence. The CB has relatively higher clay content than the MT-1 and MT-3, due to solifluction processes (French 1996), by which melting channels bring dispersed clay by erosion of snowpack's to the lowest parts of the coast, increasing the clay content close to sea level. The MT-3 does not show any clay accumulation by deposition. On the other hand, the phosphatization process contribute to clay formation in soils and its stabilization in granular aggregates (Pereira et al. 2013, Rodrigues et al. 2021, Simas et al. 2007), and increase with higher terraces.

The CEC_{pot}, PBS and Al_{sat} are good indicators to evaluate the pedogenetic evolution of the soils in the marine terrace sequence. In the studied soils, CEC and Al saturation increases and bases saturation decrease with altitude, from MT-1 to MT-3 (Table II); this behavior

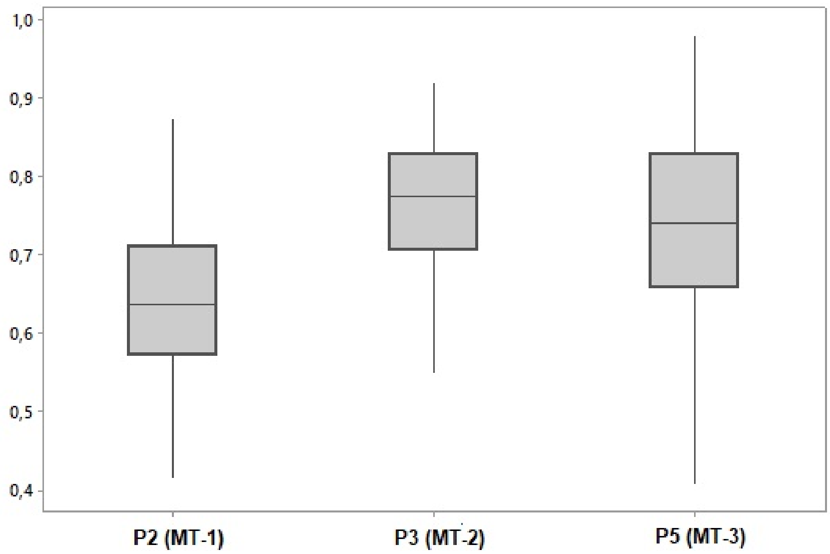

Figure 7. **Boxplot with the size of the pores of the distinct levels of marine terraces. MT: marine terrace.**

suggests a significant contribution of organic matter, generating potential acidity (H+Al), which is also consistent with increasing exchangeable Al^{3+} concentrations. High CEC values indicate greater weathering processes and nutrient release. The weathering processes associated to bird activity yield Al enrichment in these soils (Łachacz et al. 2018), by increasing acidity. Additionally, soils from MT-3 show low Fe_{OX}/Fe_{DCB} relationship in the Bw horizons, indicating a greater degree of crystallization of iron oxides, and more developed soils (Arduino et al. 1986, Wagner et al. 2007).

Statistical analyses corroborate the differences of pedogenetic processes in the studied levels. Descriptive statistical data for the contents of gravel, coarse and fine sand do not allow any separation the studied soils. However, silt and clay show significant differences, especially for P5 (see Table IV). The overall chemical composition of soils was significantly different, with average values of P, H+Al and CEC_{pot} in the upper levels (MT-2 and MT3) higher than in the lower ones (CB and MT-1); these differences are strongly influenced by bird activity. Additionally, significant differences of OM, Fe_p and Al_p demonstrate the influence of organic matter in pedogenesis of these soils (Daher et al. 2019), in line with the PCA results.

Mineralogical data corroborate the chemical attributes and show the greater development of ornithogenic soils from MT-3. The type of phosphate mineral allows distinguishing two main terrace areas: i) old abandoned terraces with negligible present-day bird activity, in which leucophosphite predominates (Tatur 1989), and ii) another zone, with intense active nesting sites, in which struvite and vivianite are the dominant phases, and birds are present.

Micromorphological and micromorphometric results helped to confirm the greater development of soils in the upper altitude levels (MT-3). The heterogeneity of coarse material composition demonstrates its allochthonous nature. All pedons are composed of volcanic fragments, from both marine origin (ice-rafted material) and fragmentation of surrounding volcanic outcrops. In all analyzed terraces, the incipient orientation of coarse materials is preferentially horizontal (Fig. 6), although more than 40 % of the grains are oriented to oblique angles (Brewer 1964, Harris & Ellis 1980).

Grain roundness and porosity allow separating MT-2 and MT-3 from MT-1. Soils from

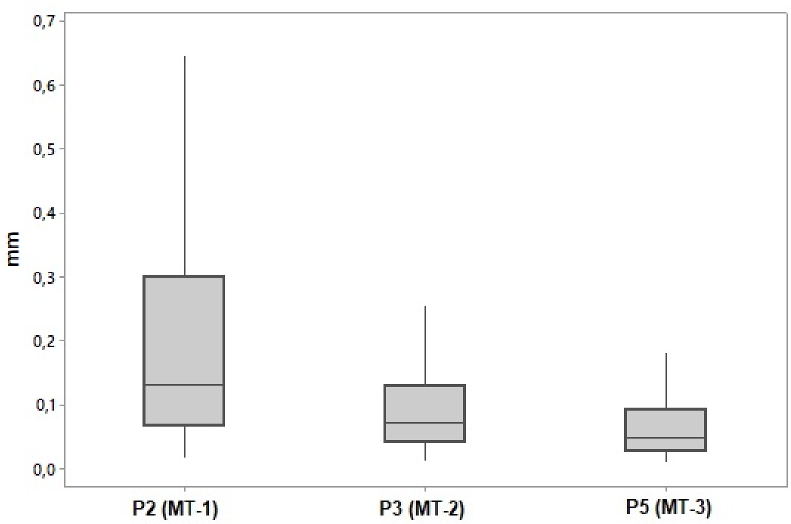

Figure 8. **Boxplot of Cox roundness indices of the grains from distinct kinds of soils. MT: marine terrace.**

MT-3 are influenced by higher pedogenetic transformations, demonstrated by the porosity, micromass and relative distribution of coarse and fine materials (Fig. 6). The diversity of relative distribution patterns indicates the performance of different soil-forming processes (Chadwick & Nettleton 1993). Grains from MT-2 and MT-3 show coating features, which implies the redistribution and illuviation of fine particles. The latter mainly occur in sandy and pebbly soils (Ugolini 1986, Locke 1986) and are influenced by freezing-thawing cycles (Schaefer et al. 2008, Van Vliet-Lanoe 2010).

Soil-landscape interplays: the Quaternary soil-time sequence

The physical, chemical, mineralogical, macro- and microphological soil properties demonstrate the existence of a soil chronosequence in HP (sense Jenny 1946). This sequence is mainly influenced by the conjugation of age of pedogenesis with altitudinal variations exposure to periglacial processes and bird activity. Advancing age also influences the nature of materials associated with the phosphatization processes.

Soil chronossequences in marine terraces of polar regions are key examples of gradual pedogenetic changes within a time-span of few thousand years in the Quaternary (Bockheim & Ugolini 1990). However, local geomorphological features of terraces can influence these soil chronosequences (Hugget 1998). The altimetric positions of marine terraces not only affect the local hydrological conditions, but also the erosion and deposition rates of each level (Meij et al. 2016, Pereverzev & Litvinova 2012), and the formation of ponds depressions and melting channels.

In marine terraces of MA, solifluction and freeze-thawing processes are frequent (French 2007, López-Martínez 2012), clearly demonstrated by micromorphological analysis, specifically the formation of a basic monic and pellicular microstructures (Schaefer et al. 2008, Simas et al. 2015). These features can be observed in all HP marine terrace levels.

The soil drainage is influenced by the distinct terrace levels. The formation of margin levees between the terraces allows the accumulation of snowpack and the formation of flooded areas. In SSI, extensive flooded areas favor soil gleization processes (Michel et al. 2014, Simas et al. 2008), but some parts of HP have good drainage conditions that favours the illuviation of fine particles downwards. Well-drained soils are only observed at the high levels, corroborated by the abundant vegetation and accumulation of organic matter. On the other hand, at lower levels, flooded areas and ponds enable the development of *Bryum spp* (Victoria et al. 2009), and little soil formation.

All marine terrace levels are influenced by bird activity, resulting in classification soils as Ornithogenic (Simas et al. 2007; Table I). Soils from MT-3 have more intense and old ornithogenic influence by present and past penguin nesting sites. With age, the same level, the vegetation growth is more stable, in close association with advanced soil development.

Biological processes associated with vegetation and bird activity are essential to the pedogenetic processes in the ice-free areas of SSI region (Bölter 2011). Both allow mitigating the periglacial and eolic erosion effects in surface areas and enable the accumulation of organic matter due to microbial activity and growth of lichens and mosses. Guano resulting from bird not only increases nutrient availability (Beyer & Bölter 2002), but also influences the chemical weathering processes and P-enrichment (Cannone et al. 2008, Barczuk & Tatur 2003, Bockheim 2015, Michel et al. 2006, Myrcha & Tatur 1991, Schaefer et al. 2008, Simas et al. 2007, 2008, Tatur & Barczuk 1985, Tatur & Myrcha 1984, 1993, Ugolini 1972). The decomposition of organic matter from guano originates acid compounds, such as nitric acid (HNO_3), which is also essential to Al-activity, chemical weathering and formation of phosphate minerals and granular microstructures. Bird activity also increases the organic matter contents, by greater development of *Sanionia uncinata* carpets and *Prasiola crispa* around the present-day nests. The capacity of vegetation to establish the upper marine terrace level indicates greater geomorphological stability, and higher soil development with age. In this concern, it is known that the combination of ornithogenic activity, high altitude and exposure time of terraces increase the chemical weathering rates in soils chronosequences (Wagner et al. 2007).

Different levels of marine terraces of SSI are associated with successive glacial isostatic uplift during the Holocene (Araya & Hervé 1972, Pallàs et al. 1995, Francelino et al. 2011), which indicate younger soils in this lower coastal landscape. At lower elevations (< 8 m), soils are classified as Gelorthents, whereas in high terraces (12-28 m), they are Humigelepts, and both showed gradual soil development upwards (Wagner et al. 2007). Similar results were reported by Haus et al. (2016), who investigated Holocene age soils (< 4 kyr BP) from eight levels of marine terraces from Livingston Island. Finally, the features of the studied soils from HP are in agreement with the Haus et al. (2016), assuming an approximate similar age in both studies.

CONCLUSIONS

1 - In HP, soils from the upper marine terraces are more developed than the lower terrace levels. This is a consequence of the greater age of exposure of the parent materials (marine sediments and volcanic rock fragments) to pedogenesis, and longer periods of bird activity, and higher number of nesting sites. Hence, higher terrace soils showed prominent chemical weathering, Fe and Al release, formation of Fe-phosphates and greater vegetation development, resulting in higher contents of organic matter and well-developed soils.

2 - Soils closer to coast show high Na and exchangeable bases elements concentrations, high amounts of primary minerals (e.g. plagioclase) and are weakly developed; hence, soils classified as Gelorthents are very common in these lower terrains. In some cases, these soils may contain clay transported from the highest terrace levels by erosion.

3 – The presence of soil chronosequence on HP is a consequence of biotic, hydrological and geomorphological phenomena, which maximize the local pedogenetic processes with increasing age. This shows the importance of using marine terraces as proxies of landscape evolution in Maritime Antarctica.

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SUPPLEMENTARY MATERIAL

Table SI. PCA loadings of select soil proprieties.

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