



SOIL SCIENCE

Soils from Byers Peninsula, Maritime Antarctic: landform-lithology controls in soil formation

JÔNATAS PEDRO DA SILVA, MÁRCIO R. FRANCELINO, ANDRÉ LUIZ L. DE FARIA, HEITOR P. PALMA, ISABELLE DE A. OLIVEIRA, JOSÉ JOÃO L.L. DE SOUZA & CARLOS ERNESTO G.R. SCHAEFER

Abstract: The Byers Peninsula, the largest ice-free area in Maritime Antarctica, is vital for studying landscape-scale natural processes due to its diverse periglacial landforms. This study aims to characterize the soils and environments of its southern sector, focusing on soil-landform-lithology interactions. Thirty-seven soil profiles were classified, collected, and chemically and physically analyzed. Principal component analysis explored relationships among variables in these profiles and 36 others from the Peninsula project database. The soils are generally shallow, with lithic or paralithic contact within the first meter. Four main soil groups were identified: patterned-ground soils on plateaus, ornithogenic soils, non-ornithogenic soils, and non-ornithogenic sodic and sandy soils on beaches and marine terraces. The Peninsula, divided into six geological units, represents a diverse periglacial morphogenetic system. Sixteen landform types were identified, each associated with different processes, topographies, lithologies, altitudes, and orientations, highlighting the importance of periglacial morphogenesis. Stable soils, such as upper cryoplanation platforms, raised beaches, volcanic plugs, and ornithogenically influenced areas, show greater soil development and weathering. In contrast, dynamic periglacial landforms like scree stony slopes and talus exhibit minimal soil development and instability. The Byers Peninsula's pedodiversity is due to its varied lithologies, landforms, extensive ornithogenic influences from seabirds, and long-term vegetation establishment.

Key words: Pedoenvironments, geology, geomorphology, periglacial landforms, ice-free area.

INTRODUCTION

In the last two decades, there has been a growing number of studies on the soils and geomorphology of maritime Antarctica (Balks et al. 2013, Francelino et al. 2011, López-Martínez et al. 2012, Michel et al. 2006, Moura et al. 2012, Navas et al. 2006, 2008, Schaefer et al. 2008, Simas et al. 2006, 2008, Vieira et al. 2023). Although this work has been crucial for a better understanding of the main soil types and soil formation processes in this region, there is

no published information on the coexisting relationships between lithology, landforms and soils.

Livingston Island, the second largest island in the South Shetlands Archipelago, Maritime Antarctica (Zidarova et al. 2010), in which the Byers Peninsula (BP) is located, has a very diverse and complex geological sequence compared to the other islands in the archipelago. Its formation and structuring is the result of the process of subduction between tectonic plates

over time (Storey & Garrett 1985). The geology of BP is predominantly made up of Paleo-Mesozoic claystones, Juro-Cretaceous conglomerates, pyroclastic rocks interspersed with Cretaceous basalt, dykes and sills of Paleogene andesitic basalt-basalt composition and Quaternary volcanic or sedimentary rocks (Alfaro et al. 2010, Hobbs 1968, Smellie et al. 1980).

Polyphasic origin of the landforms in ice-free areas is the result of the interaction between glacial, paraglacial and periglacial processes (Davies et al. 2013). The Byers Peninsula, considered the largest ice-free area in Maritime Antarctica due to the retreat of the main glacier, Rotch Dome, has a great diversity of periglacial landforms, such as felsenmeers, patterned ground, rock-glaciers, and uplifted marine platforms, and it has been indicated as an international reference site for studies on natural processes at landscape scale in Maritime Antarctica (Quesada et al. 2009).

Maritime Antarctic soils vary according to lithology and geology (Michel et al. 2014, Navas et al. 2008, Rodrigues et al. 2019). However, the contribution of lithological diversity to the evolution and modulation of periglacial environments is still poorly studied (Lopes et al. 2021), taking the interactions between landscape and soil as the basis for understanding the importance of these substrates (de Souza et al. 2012, Francelino et al. 2011, Lopes et al. 2021, Michel et al. 2014, Moura et al. 2012, Rodrigues et al. 2019). The lithologies at the Byers Peninsula vary from sedimentary (marine mudstones, sandstones and conglomerates) to volcanic and volcanoclastic rocks, intruded by different igneous bodies (Moura et al. 2012).

Studies on geomorphology and soil distribution already exist on other islands of the Maritime Antarctica. However, the interaction between these elements and the lithology on Byers Peninsula is non-existent. This area is

of high geological and biological value as it contains complete records of juro-cretaceous rocks from the Atlantic magmatic arc and is one of the areas with the greatest diversity of terrestrial biota in Antarctica.

In this context, understanding these landscapes through a thematic analysis allows us to understand the current and past processes. The Antarctic landscape, especially in warmer and wetter areas such as Maritime Antarctica, has experienced different situations during its formation that have given it its physical, chemical and biological characteristics. Elements of the physical and biotic environment, such as geology, geomorphology, climate, vegetation cover and soils provide us with information about the past, the present and trends for the future. Thus, the aim of this study was to characterize the soils and environments of the southern sector of the Byers Peninsula, Livingston Island - Maritime Antarctica, in terms of soil-landform-lithology interactions.

MATERIALS AND METHODS

Study area

The Southern Byers Peninsula (BP) is located at the western end of Livingston Island (60° 56' - 61° 12' W and 62° 34' - 62° 41' S), part of the South Shetlands Archipelago, Maritime Antarctica (Figure 1). The peninsular area is approximately 61 km², corresponding to the largest ice-free area in Maritime Antarctica (Hobbs 1968). The climate is polar maritime, with an average annual temperature of -2.8 °C at 70 m above sea level (m.a.s.l.) and annual rainfall ranging from 500 to 800 mm (Bañón et al. 2013). The area is identified as a habitat of global importance, as it is home to breeding colonies of terns (*Sterna vittata*), gulls (*Larus dominicanus*), penguins (*Pygoscelis antarctica* and *Pygoscelis papua*), petrels (*Oceanites oceanicus*, *Fregetta tropica*, *Daption*

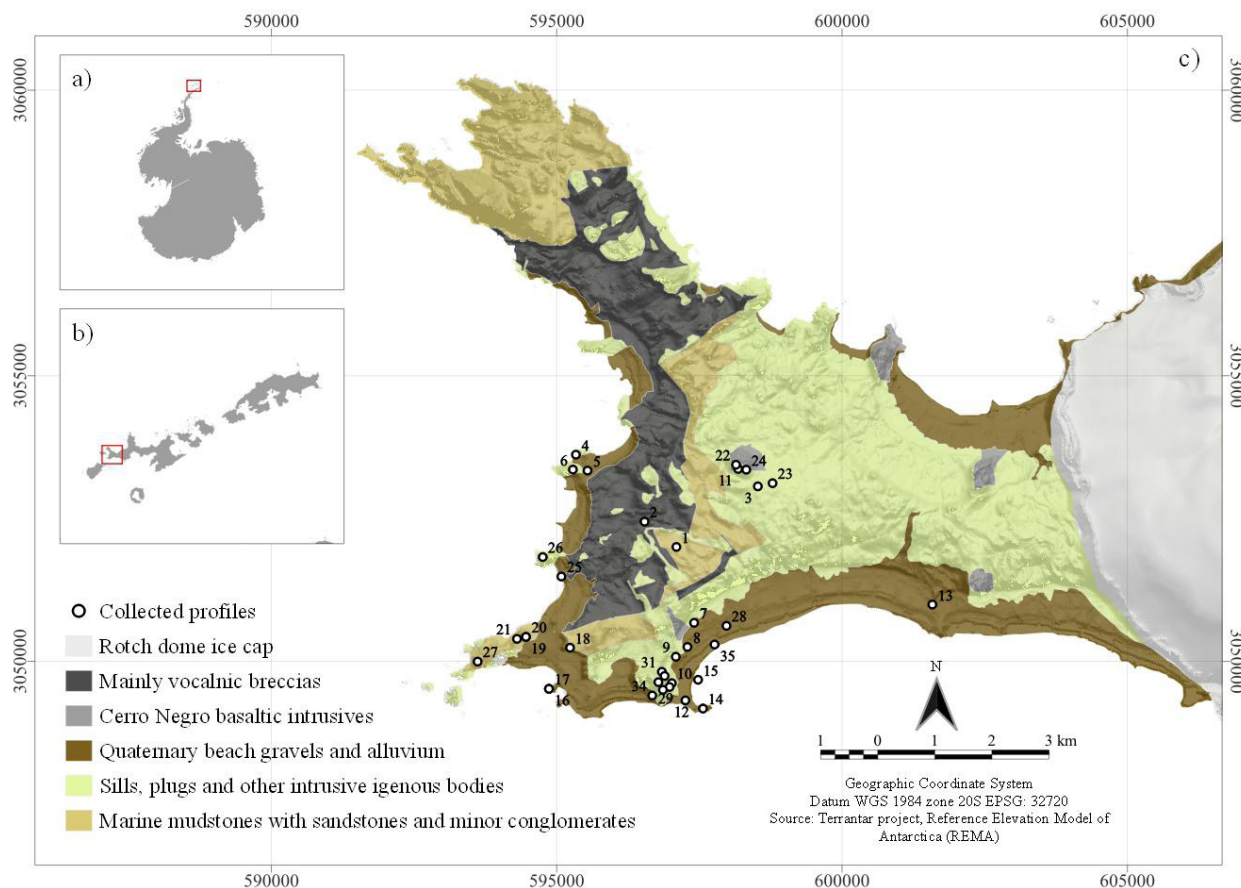


Figure 1. Distribution of soil profiles collected in Southern Byers Peninsula, Livingston Island overlapping the geological units.

capense and *Macronectes giganteus*), shags (*Phalacrocorax atriceps*), skuas (*Stercorarius antarcticus*), Antarctic doves (*Chionis albus*) (Harris et al. 2015) and intense occupation by elephant seals (*Mirounga leonina*). BP is also the most important limnological site in the region and the most vulnerable to human interference. Because of its uniqueness, BP is part of ASPA N°. 126 and has a special environmental protection regime under the Antarctic Treaty System (Oliva et al. 2016).

Geomorphological and lithological characterization and mapping

Geomorphological features and processes were described according to field observations, interpretation of topographic data (Alfaro et al. 2010). The main lithologies present in the BP

described in the literature were observed in the field and contrasted with the geomorphological processes and features and the distribution of soils. The digital elevation model and slope model, derived from contour lines using ArcGis software, helped to identify the geoforms and quantify the morphometric parameters. A geomorphological map (scale 1:30,000) was produced to represent the spatial variation of glacial, periglacial, fluvial, marine and structural features in the study area.

Soil sampling and characterization

Thirty-seven soil profiles were collected according to the recommendations of Antarctic Permafrost and Soils (ANTPAS), representing the geological and pedological diversity of BP. The

profiles were described and classified according to Soil Taxonomy and the World Reference Base for Soil Resources. The profiles were dug until they reached the lithic contact or the level of the permafrost. A 200 cm control section was used for the deeper soils.

The soil samples were air-dried, crumbled and sieved through a 2 mm sieve prior to routine analysis of the soil's texture and chemical properties (Teixeira et al. 2017). The sand, silt and clay contents were determined using the sieve-pipette method, after dispersion with 0.1 mol L⁻¹ NaOH. Soil pH was measured with a glass electrode in a 1:2.5 v/v suspension of soil and deionized water. Potential acidity (H + Al) was extracted in a 1 mol L⁻¹ solution of ammonium acetate at pH 7. The exchangeable contents of Ca²⁺, Mg²⁺ and Al³⁺ were determined in a 1 mol L⁻¹ KCl extract. The exchangeable K⁺ and Na⁺ contents were determined by extraction from a Mehlich-1 solution. From these results, the sum of bases (SB), base saturation (V%), aluminum saturation (m%) and cation exchange capacity (CEC) were calculated for each sample. The extractable phosphorus content (total P) was determined in a Mehlich-1 solution. The ability of soil to adsorb P was determined after shaking 2.5 g of soil for 1 h in a 0.01 mol L⁻¹ CaCl₂ solution containing 60 mg L⁻¹ of P. The suspension was filtered and the P remaining in the solution (Prem) was determined by photolorimetry (Alvarez et al. 2000). Prem is a measure of clay reactivity, and low values are associated with an abundance of low crystallinity minerals and iron oxides with an affinity for P. All results are presented as a weighted average of the results from the thickness of each horizon.

Descriptive statistics

Principal Component Analysis (PCA) was carried out to clarify the correlation between the variables. PCA consists of a variable reduction

method that produces a smaller number of artificial and uncorrelated variables, called Principal Components (PCs). The PCs are listed in descending order of explanatory power of the variance of the data. Prior to PCA, the analytical data was log-transformed and standardized (McKilup & Dyar 2010, Wackernagel 2003).

For the final composition of the PCA, in addition to the data obtained from the 37 soil profiles collected and investigated in this study, further chemical and physical database of the soils collected in the published studies by da Silva et al. (2022) and Moura et al. (2012), referring to other parts of the peninsula, were incorporated, to provide a more precise grouping and spatialization of parameters. In total, the physicochemical characterization of all horizons/layers collected in the 73 profiles (Figure S2) in the BP was used in the PCA.

RESULTS

Soil profiles

The profiles collected were classified by the WRB (Soil Taxonomy) system as Leptosol (Entisols; 18 profiles), Regosol (Entisols; 11), Cryosol (Gelisols; 7) and Histosol (Histosols; 1) (Table I). The detailed description of the chemical and physical characteristics of all the horizons collected in the 37 profiles are described in Table S1. Five geological complexes where the soils were formed were identified (Figure 1).

The soils of the Byers Peninsula are shallow, generally with lithic or paralytic contact in the first meter. Another common feature is the high gravel content, resulting in skeletal and poorly developed horizons. There is variation in the intensity of cryoturbation, the influence of orithogenesis and the reactivity of the soil according to the sampling site.

Based on morphological, physical and chemical characteristics, four main groups

Table I. Chemical and physical characterization of the profiles collected and descriptive statistics of the profiles (mean values weighted by the thickness of the horizons in each profile) and soil groups (median - coefficient of variation %) of the Byers Peninsula.

Profile (altitude)	depth	T ^(a)	Wet soil color ^(b)	Cs	Fs	Silt	Clay	Texture ^(c)	pH	P	Ca ²⁺	Mg ²⁺	Al ³⁺	H ⁺ +Al ³⁺	SB	t	CEC
	(cm)	(°C)		%						mg dm ⁻³		cmolc kg ⁻¹					
P11 – Leptosol Oxiaquic (67 m)	60	2.4	10 YR 4/1	59	10	16	14	SL	7.1	27.7	11.2	2.9	0.0	0.9	15.3	15.3	16.1
P12 – Skeletic Leptosol Turbic (92 m)	45	1.5	10 YR 3/3	28	48	16	8	LS	7.9	32.2	4.4	4.1	0.0	1.0	10.6	10.6	11.5
P30 – Skeletic Regosol Gelic (103 m)	50	1.2	10 YR 3/1	28	26	36	10	L	8.0	33.1	5.7	4.6	0.0	0.5	12.0	12.0	12.5
P36 – Skeletic Leptosol Humic Turbic (71 m)	50	1.3	10 YR 2/2	33	25	33	9	SL	7.4	70.1	8.6	6.0	0.0	2.5	15.7	15.7	18.2
Patterned-ground soil on abrasion platform (4)	50-12	1.4-34	-	31-40	25-56	25-42	10-27	-	7.6-5	32-48	7-40	4-30	0-	0.9-74	14-19	14-19	14-21
P2 – Skeletic Leptosol Humic (188 m)	30	2.3	10 YR 2/2	47	20	19	14	SL	7.0	20.0	4.5	3.1	0.0	3.5	9.5	9.5	13.0
P4 – Lithic Leptosol Gelic (78 m)	48	2	10 YR 3/3	49	12	24	15	SL	6.7	69.0	5.8	5.1	0.4	6.7	12.4	12.8	19.1
P5 – Histic Leptosol Gelic Turbic (35 m)	30	4.2	10 YR 5/1	28	18	31	24	L	5.5	34.1	4.2	2.0	2.1	12.5	7.3	9.4	19.8
P6 - Turbic Cryosol (45 m)	70	0.7	7.5 YR 4/2	48	12	26	15	SCL	6.0	114.0	2.1	2.0	0.5	10.6	5.2	5.7	15.8
P7 – Skeletic Leptosol Humic (85 m)	40	3	10 YR 2/1	44	26	17	13	SL	6.9	20.8	2.0	2.3	0.0	5.3	6.0	6.1	11.3
P10 – Lithic Leptosol Gelic (70 m)	30	4	10 YR 4/1	44	10	23	23	SCL	7.0	67.9	9.3	5.2	0.0	2.3	16.0	16.0	18.3
P14 – Leptic Sodic Regosol Humic (20 m)	80	4.4	7.5 YR 2/2	66	10	9	15	SCL	6.3	101.3	5.6	1.9	0.1	2.8	9.6	9.7	12.4
P16 – Leptic Regosol Humic (10 m)	40	0.8	7.5 YR 2.5/2	7	3	2	2	SL	1.6	5.8	1.3	1.2	1.0	1.8	1.6	1.6	2.4
P18 – Dystric Leptosol Humic Sodic (10 m)	40	3.1	10 YR 3/4	60	10	14	16	SL	5.4	80.6	2.0	0.8	1.5	9.8	4.0	5.6	13.8
P26 – Leptic Regosol Turbic (23 m)	110	2.8	10 YR 4/4	14	7	34	45	C	4.3	5.9	7.4	1.8	10.4	35.4	10.1	20.5	45.5
P34 – Skeletic Leptosol Gelic (79 m)	12	5.6	7.5 YR 2.5/1	61	16	19	4	LS	7.8	12.6	12.9	6.7	0.0	0.5	23.1	23.1	23.6
P37 – Skeletic Leptosol Humic (132 m)	30	4.9	10 YR 2/1	45	26	20	10	SL	6.8	11.3	1.7	1.7	0.0	4.3	4.5	4.5	8.8
Shallow and deep non-ornithogenic soils (12)	40-58	3-48	-	46-41	12-51	19-44	15-68	-	7-27	27-86	4-72	2-65	0.2-219	5-118	8-65	10-63	15-62

Table I. Continuation.

P 1 - Skeletic Leptosol Gelic Ornithic Stagnic (128 m)	30	3.5	10 YR 3/2	33	22	34	11	SL	7	179	5	2	0	5	9	9	13.2
P3 – Skeletic Dystric Histosol Ornithic Turbic (28 m)	100	3	7.5 YR 2.5/1	65	14	11	10	LS	5.0	241.2	0.5	0.1	1.7	13.7	1.6	3.3	15.4
P8 – Turbic Leptic Cryosol Humic Ornithic (14 m)	90	0.7	7.5 YR 2.5/3	43	19	18	20	S	5.1	81.9	0.5	0.3	0.8	15.7	2.7	3.4	18.3
P13 – Skeletic Umbric Leptosol Ornithic (5 m)	20	5	10 YR 2/1	67	8	10	16	SL	6.0	148.1	5.6	6.6	1.3	11.0	15.1	16.5	26.1
P15 – Skeletic Umbric Leptosol Ornithic (68 m)	15	4.5	7.5 YR 2.5/3	63	12	13	12	SL	4.7	284.9	2.9	3.3	4.9	28.0	9.5	14.4	37.5
P17 – Stagnic Sodic Regosol Ornithic (10 m)	60	3.4	10 YR 2/2	73	4	14	10	SL	5.1	172.3	0.6	0.2	3.0	13.0	2.3	5.3	15.3
P19 – Skeletic Leptosol Ornithic (10 m)	20	4.5	7.5 YR 2.5/2	71	9	10	11	SL	5.3	282.2	0.7	0.3	1.3	13.7	2.3	3.6	15.9
P21 – Lithic Leptosol Ornithic (28 m)	20	3.8	7.5 YR 2.5/2	64	10	20	7	SL	6.1	139.9	2.5	1.8	0.3	8.4	5.9	6.2	14.3
P22 – Lithic Leptosol Ornithic Sodic (6 m)	12	3.8	10 YR 2/2	79	3	5	13	SL	4.9	252.8	1.7	1.1	0.5	12.6	6.9	7.4	19.5
P23 – Lithic Leptosol Ornithic Sodic (4 m)	20	3.3	10 YR 2/1	81	2	5	12	LS	5.1	479.5	2.0	0.9	0.2	10.8	6.0	16.8	0.0
P24 – Leptic Sodic Regosol Ornithic (2 m)	35	4.3	7.5 YR 2.5/1	76	7	11	5	SL	6.9	86.3	13.8	1.7	0.7	5.1	18.3	19.0	23.3
P25 – Leptic Sodic Regosol Ornithic (1 m)	45	4.9	7.5 YR 2.5/2	77	6	11	6	SL	7.5	85.2	13.6	2.3	0.0	0.8	20.4	20.4	21.1
P27 – Dystric Leptosol Humic Ornithic (46 m)	40	0.4	7.5 YR 2.5/3	55	19	13	13	SL	5.0	112.2	1.2	0.9	1.8	13.8	2.8	4.7	16.6
P28 – Dystric Leptosol Humic Ornithic Sodic (32 m)	40	2.7	7.5 YR 4/3	53	14	15	18	SL	5.2	615.7	4.7	2.4	2.9	22.2	9.3	12.1	31.5
P29 – Dystric Leptosol Humic Ornithic Sodic (34 m)	50	3.7	7.5 YR 3/3	56	10	20	15	SCL	4.2	1301.2	1.7	0.4	2.1	37.2	5.8	7.9	42.9
P31 – Leptic Skeletic Regosol Ornithic (130 m)	40	2.7	10 YR 2/2	36	21	29	14	L	7.2	394.4	5.6	3.8	0.0	3.9	10.6	10.6	14.5
P32 – Eutric Leptosol Humic Ornithic Sodic (14 m)	30	3.4	10 YR 2/2	36	13	22	29	CL	7.0	242.8	11.3	1.9	0.0	2.0	14.4	14.4	16.4
P33 – Lithic Leptosol Gelic Ornithic (45 m)	13	7.2	10 YR 3/1	55	11	17	18	SL	7.1	25.4	10.4	10.7	0.0	1.6	25.5	25.6	27.1
Shallow and deep ornithogenic soils (18)	30-67	3-42	-	63-24	9-53	14-48	13-40	-	5-18	241-143	3-96	2-120	0.7- 106	12-75	7-73	9-59	18- 47
P9 – Regosol Gelistagnic (3 m)	70	3	10 YR 3/3	83	3	6	8	LS	6.1	42.1	1.1	1.3	1.2	7.6	7.4	8.6	15.0
P20 – Sodic Regosol Gelic (2 m)	80	3.3	7.5 YR 2.5/1	80	9	4	7	LS	5.4	167.4	1.4	1.7	0.4	4.8	12.8	13.2	17.5

Table I. Continuation.

P35 – Leptic Regosol (4 m)	60	1.9	7.5 YR 2.5/3	82	8	6	4	LS	6.6	52.9	2.6	2.2	0.1	3.1	7.8	7.9	10.9
Eutrophic sandy beach soils (3)	70-15	3-27	-	82-2	8-51	6-25	7-34	-	6-9	53-79	1-46	2-27	0.4- 102	5-44	8-31	9-29	15- 23

(a) Temperature measured in the deepest horizon; (b) diagnostic horizon; (c) C/ Clay; L/ Loam; LS/ Loamy Sand; S/ Sand; SL/ Sandy loam; SCL/ Sandy Clay loam.

of soils have been identified on the Byers Peninsula (Table I): a) patterned-ground soils developed on plateaus; b) ornithogenic soils; c) non-ornithogenic soils; d) non-ornithogenic sodic and sandy soils developed on beaches and marine terraces. Soils with pattern-ground are found in the highest part of the landscape (above 70 m.a.s.l.), on abrasion platforms that have become residual plateaus due to the action of morphogenetics agents. These soils have a pH above 7.0, a light or rather sandy texture, are shallow, eutrophic, have sparse vegetation cover and have no bird activity.

The soils developed on the uplifted marine terraces or fluvial-glacial plains presented diverse depth, with a loamy texture and varying degrees of nesting. Ornithogenic soils are generally the shallowest soils found on the Byers Peninsula, with the highest values for temperature at depth, phosphorus and loamy or sandy texture. The pH and eutrophy values vary between abandoned and active penguin colonies. All the profiles with records of ornithogenesis above 20 m were identified in the field as paleoenvironments that were uplifted as an isostatic response to the retreat of the glacier. The non-ornithogenic soils have an alkaline pH, a P content nearly 50 mg kg⁻¹ and are predominantly eutrophic. The beaches make up 6% of the area of the Byers Peninsula and have extensive sandy and gravelly strands. The soils formed here are sandy, sodic, eutrophic and have no nesting sites.

Due to active periglacial erosion, with a marked influence from the processes of

solifluction and frost creep, only 27% of the Byers Peninsula is stable enough to allow further soil development, while the remaining 73% is made up of unstable and sloping areas.

Geology compiled and interpreted

Livingston Island has one of the most diverse and complex geological sequences in the South Shetlands, directly reflected in the variety of lithologies identified, such as: gondwana sedimentary rocks from the Upper Paleozoic-Lower Mesozoic, sedimentary rocks (clastic rocks - conglomerates) from the Upper Jurassic-Lower Cretaceous, volcanic rocks from the Cretaceous, Paleogene Plutonic rocks to Quaternary or recent volcanic or sedimentary rocks (Hobbs 1968, Smellie et al. 1980).

In general, Byers Peninsula is subdivided into 6 geological units (Table II – Figure 1). Periglacial erosion on Byers Peninsula is responsible for redistributing and mixing a large part of the physical weathering products of the rocks, obliterating the geological contacts in smoother reliefs. However, a good separation of the main lithologies is possible in the field.

On Byers peninsula we find one of the most extensive and developed systems of beaches and raised marine terraces. These currently occupy five different uplifted plateaus, with successively older sediments, although all date back to the Holocene. In the central and eastern part of the peninsula, continental strata of the so-called Byers Group emerge (Hathway 1997, Parica et al. 2007), which correspond to the Cerro Negro formation. The units of the Cerro Negro

Table II. Geological units on the Byers Peninsula.

Geology	Area (ha)	Area (%)
Quaternary beaches and terraces and alluvial fans (Quaternary-Pleistocene and Holocene)	1399	16.77
Continental volcanic tuffs and breccias (Lower Cretaceous)	103	1.23
Sills, volcanic chimneys and intrusive igneous bodies	2481	29.75
Marine Sediments - Argillites, Sandstones and Conglomerates	1018	12.2
Volcanic breccias	1049	12.6
Rotch Glacier Ice Sheet (undifferentiated Quaternary)	2289	27.45

formation are based on differential angular discordance over marine and transitional sediments of the Chester Cone and Presidente Beach formations.

One of the most characteristic features of the Peninsula's central landscape is Mount Chester, an andesitic intrusive body with associated pyroclastic flows and flows. The outcrops of the Cerro Negro Formation extend from this area to the Domo Rotch Glacier.

The continental sedimentation is made up of conglomeratic, sandy and pelitic facies of light and green colors, with a great deal of intercalated pyroclastic material. The pyroclastic units outcrop in the central-eastern sector of the peninsula and around Cerros Chester and Don Carlos.

The sedimentary rocks of the Cerro Negro Formation are interspersed with outcropping volcanic sequences around Cerro Negro. The profile comprises two sections, separated laterally by faulting. The lower section is approximately 35 m thick and rests on a basaltic volcanic rock. The upper section, approximately 45 m thick, is at the base of a pyroclastic deposit which marks the intercalation of a volcanic event concomitant with sedimentation.

Contemporaneously with volcanism, a large quantity of fluvial clastic sediments of varying granulometry accumulated in the middle

sector of the peninsula. The interpretation of this environment allows us to recognize several basins with continental characteristics, developed in stable climatic conditions with strong initial energy ("dissecting" the volcanic, plutonic and sedimentary material present in the area) and which then decreases allowing the development of lakes.

Noteworthy is the large area of beaches and fluvio-glacial plains with Quaternary alluvial fans and terraces, which indicate the strong glacioisostatic uplift of the Byers Peninsula, caused by the retreat of the Rotch glacier. They are most developed in the southern part of the peninsula, but are distributed all along the coast.

In the western sector of the peninsula, there are extensive areas of Mesozoic marine sediments (12.2%), especially siltstones and claystones, which condition acidic soils with poor vegetation development and strong periglacial erosion.

The central and most extensive part is the volcanic axis with sills, chimneys and intrusive bodies that dominate the top landscape. Truncated by glacial or marine erosion before uplift. They occupy almost 30% of the mapped area. The dominant periglacial processes in Byers are: gelifluction, cryoturbation, with minor contributions from chemical weathering and

areas of wetting and drying. They all occur in a context of strong and active glacio-isostatic uplift. Thus, Byers Peninsula represents a typical periglacial morphogenetic system, perhaps the most typical and diverse in maritime Antarctica.

Geomorphology of the Byers Peninsula

The Byers Peninsula has been ice-free since at least the great Holocene retreat of the South Shetlands glaciers, around 4,000 years B.P. (Björck et al. 1993, Lopez-Martinez et al. 1996, Serrano & López-Martínez 2000). The greater humidity experienced in the region since then has greatly favored periglacial processes, creating a variety of associated geoforms (Figure S1), many of which are still active, while others are relict or fossil.

The geomorphology of the Peninsula (Figure 2 and Table III) was constructed from the Byers Geomorphology map (Lopez-Martinez et al. 1996). The landform patterns were built up over

the last 10,000 years (Holocene) as a result of the retreat of the Roch Dome glacier. These areas, which had previously been shaped by glacial action, began to receive periglacial weathering and morphogenesis.

It was possible to differentiate 16 types of landforms associated with different processes, topographies, lithologies, altitudes and orientations, which show the importance of periglacial morphogenesis in maritime Antarctica (Table III). The landforms of periglacial origin occupy an area of 8,359.3 ha, which corresponds to 100% of the extension of the ice-free areas of the Byers Peninsula. Patterned surfaces were the dominant geoform, occupying 28.4% of the ice-free area, followed by cryoplanation platforms (12.9%), indicating the dominance of the area's gentle relief due to ancient ice retreat.

Plateaus with slight topography between 70 and 190 m.a.s.l., poor drainage and the accumulation of water derived from melting

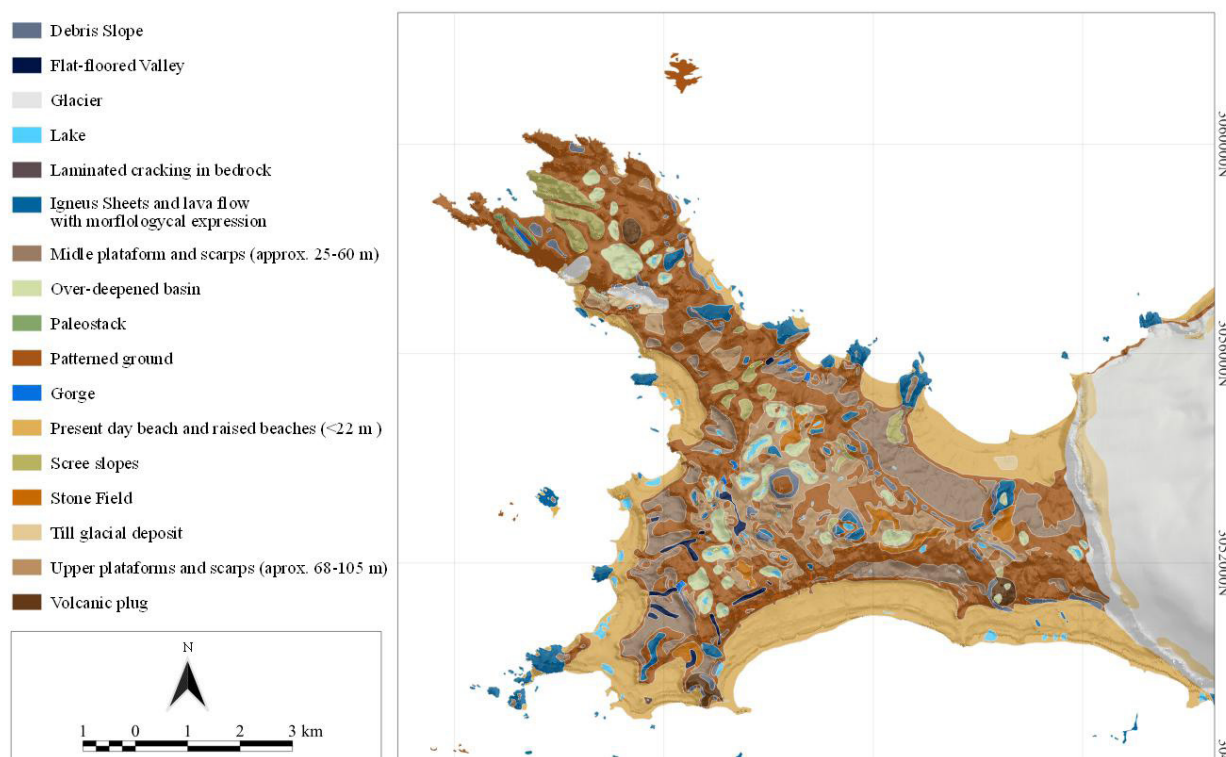


Figure 2. Geomorphological map of the Byers Peninsula, Livingston Island.

ice during the summer favor the development of patterned grounds and stone circles. Cryoturbation is common on plateaus above 70 masl, while solifluction is observed on steep slopes. Gelifluction is a process concentrated in the northern part of the Peninsula, originating debris lobes on the slopes of the highest hills. They are evident in the contact between plutonic igneous rocks and Quaternary sediments from the uplifted marine terraces.

The absence of vegetation on patterned ground and the thermokarst in areas at 100 m.a.s.l. indicate that these forms are not stable at present. In turn, the well-developed vegetation cover on patterned grounds below 70 m.a.s.l. suggests that these forms are not active. Good drainage on platforms below 30 m.a.s.l. suggests the absence of permafrost associated with uplifted marine terraces.

The geomorphological processes at work in periglacial areas are highly specific, as are the

landforms generated. From a morphodynamic point of view, these areas are fundamentally characterized by the alternation of ice and thaw on their surface. Their action is concentrated in the transition period between winter and summer, due to the intense temperature variation around 0 °C.

From a geomorphological point of view, the main resulting forms are the Felsenmeer, slopes, moraines, talus and rock outcrops. The depositional ones are linked to the plateaus, where, depending on the slope, patterned soils, fluvioglacial plains and uplifted marine terraces are found.

Periglacial features and geoenvironments

Polygonal soils

The Byers Peninsula is home to the most extensive areas of *polygonal soils* (patterned-ground – Figure S1a). *Polygonal soils* are generated in

Table III. Geomorphological units mapped on the Byers Peninsula.

Landforms	Area in hectares	Area (%)
Stony slopes (clast mantles)	258	3.42
Embedded open valleys	43	0.51
Glaciers	2102	25
Gorges	8	0.1
Lava terraces	134	1.6
Lakes	61	0.75
Felsenmeer	107	1.27
Cryoplaning platforms over 60m	1084	12.9
Thrust moraines	5	0.05
Thermokarst	250	3
Uplifted marine volcanic remnants	0,3394	<0.05
Patterned soils	2358	28.4
Volcanic plugs	118	1.42
Present-day beaches and Holocene paleo-beaches	1583	19
Bottom moraines	199	2.5
Association of volcanic plugs, patterned soils and rubble slopes	49	0.6

the active layer above the permafrost and are classified by their geometric shape into circles, polygons, nets and bands (Washburn 1956). The circles are between 0.5 and 3 m in size. The soils have a high content of fine material in their central part and the edges are circled by stones.

On the upper abrasion platforms, above 80 meters, there is an extensive area with marked development of *polygonal soils*, showing the antiquity of this periglacial feature on the Byers Peninsula. The instability of the permafrost can be seen in the presence of thermokarst depressions, denoting the current warming trend.

Polygonal soils are widespread in Maritime Antarctica. Circles, polygons, and stripes are the most common types found in cryoplanated plateaus, summit of cliffs, and slopes on basalts (Michel et al. 2014, Francelino et al. 2011), andesites, and tuffs (Oliva et al. 2019, Rodrigues et al. 2019). These features are less common on sedimentary rocks and sandy soils on raised beaches (Schaefer et al. 2015), suggesting a minimum clay content is necessary to favor water and clay migration during soil dissection in the winter. The thermal and humidity gradients in the active layer and top of permafrost induce clay migration from deeper horizons to the surface and the segregation of coarse particles (Hallet et al. 2011).

Striated soils are polygonal soils of stripes more or less parallel to the line of maximum slope of the hillside (Figure S1c). The striations alternate between clasts and finer material. The size of the clasts decreases with depth (up to 1m). In the case of the Byers Peninsula, the striated soil fields form slopes below the rocky rubble talus with increasing alignments and lobate shapes as the slopes increase in steepness, and the polygons are no longer stable, becoming elongated and dynamic. Contributing to the process are internal periglacial actions,

permafrost associated with solifluction as a function of slope. Vegetation cover is incipient, and many crustose lichens show the mark of the erosion process. *Cracked soils* form due to thermal contraction, as the temperature of frozen soils decreases (Figure S1b).

Fluvioglacial plains and canyons

The Byers Peninsula is home to well-developed river systems, with large channels and lakes. These form remarkably developed anastomosed marine fluvioglacial systems, due to the extensive plain relief. In the coastal areas where thaw channels flow down from the highest platform, canyons and alluvial fans are formed which dump and deposit sediments from the interior of the Peninsula, forming typical fluvioglacial plains with anastomosed drainage (Figure S1d).

In some cases, small deposits and moraines form at the outlet of these canyons, indicating the existence of small cirque glaciers in some of the valleys that break through the steep platform. In the most stable parts of these plains, between the second-level marine terraces and the beaches, moss fields and discontinuous *Deschampsia* coverings are common. There are many skeletal remains of elephant seals and penguins, as well as whale bones buried in the terrace sediments, exhumed by fluvioglacial erosion.

Erosive features

Felsenmeers are features composed of outcropping rocks strongly gelifRACTURED. The deposit is formed by a strong contribution from cycles of freezing and thawing of the water in the rocks (cryoclastism) (Figure S1f). It is an area of periglacial morphogenesis, where in situ physical weathering is dominant.

They are rock platforms or banks derived from cryoclastic phenomena, due to strong post-glacial physical weathering. Most *felsenmeer* are

flattened on high ground and are present on structural surfaces, where incipient polygonal soils can develop. Physical disintegration results in fragments of different sizes, depending on the intensity of fractures and joints.

The physical decomposition of rock by gelifraction is the most important weathering process in periglacial zones. It is also called cryoclastic weathering or gelivation. Cryoclastis is a determining factor in the fractionation of rock outcrops in the South Shetlands, given that there are enough ice-thaw cycles to break up the substrate. At the base of felsenmeer areas, where there is a lot of blockfall, talus is formed (Figure S1f).

Talus are very common geoforms that surround the large basaltic volcanic hills or form bangs on the peninsula's structural escarpments (Figure S1e). They are characterized by the presence of large, angular fragments of igneous rock in a well-drained environment due to the presence of coarse material, exposure to winds and steep slopes, which gives the feature strong erosive dynamics. They occur mainly around the outcrop belt of volcanic residuals in the form of basaltic rock cones. The most imposing talus in Byers are found on the north and west faces of Sealers Hill and on the Ray promontory, where basaltic escarpments undergo cryoclastis and provide the clasts that line the beaches and terraces.

The most common geomorphological unit on the Peninsula (Figure S1g), *scree stony slopes* have varying degrees of cryoturbation, sometimes forming stone stripes or sparse vegetation.

They are made up of a surface layer of rock fragments, rounded or angular blocks mixed chaotically with the silty matrix. The clasts are arranged or accommodated horizontally, which differentiates them from the rougher and rougher surfaces of the felsenmeer. Formed

either by slow gelifluxion or solifluxion, they occur on gently undulating terrain where the process of erosion by solifluction and mass movement is active during the thaw period. This geoform occurs in various lithologies, but predominates in volcanic tuffs, where it tends to form laminar chips. It occupies most of the periglacial features mapped in Byers, and may show locally variable hydromorphism. The seasonal dynamics of the active layer in these geoforms is extreme, as a result of the intense mobilization of the soil downslope. They form wide segments that connect the upper platforms to the lower levels of the landscape.

The *vulcanic plug* correspond to residual and resistant features that occur throughout the peninsula. They express higher resistance of rocks to weathering due to the geological structural and massiveness (Figure S1h). These features are widespread in Maritime Antarctica and correspond to the highest altitudes.

Beaches and raised beaches

On the western edge of the Byers peninsula, five levels of *raised beaches* are visible, three of which are generally easily observable, graded from a height of 45 meters to the current sea level (in these areas we find algae deposits more than 1 m deep – Figure S1j). The terrace material subject to marine erosion looks like “pebbles”, although fragments from different angles are mixed together. In the higher parts of the *raised beach* levels, there is a talus cover that descends from the cliffs and covers part of them. Traces of human occupation (seals and whale hunters) are common on the higher levels of the terraces, next to the basalt rocks that served as temporary shelter.

The *raised beaches* are up to 1200m wide (Figure S1k). The stability of the edges of the terraces is maintained by strings of pebbles and basalt cliffs. In the areas where meltwater

accumulates, fields of bryophytes develop and, in the more frontal strips near the beach, clumps of *Deschampsia* are found, especially in areas where birds are present.

The *beaches* of the Byers Peninsula occupy 19% of its area and feature extensive sandy and gravelly strands alternated with strips of beaches with pebbles, cliffs and erratics, interspersed with pebbles of different composition and size, many of lithologies that do not occur in Byers, associated with the presence of coarse and medium sand, as well as silt in the lower depressions and calm waters (Figure S1k). In addition to the current beaches, on all levels and terraces there are erratic blocks foreign to the peninsula's substrate, from nearby glaciers or stranded icebergs, scattered randomly on the lower terraces and beaches. A unique and very expressive feature of the Byers beaches is the enormous deposition of giant seaweed (*Desmarestia*, etc.), forming true dark algal peat bogs, stabilized by the constant movement of elephant seals over this beach level.

The intensity of glacio-isostatic uplift could be assessed by the presence of abandoned sub-tidal beaches located about 1.5 m above the current beach, with a thick layer of macroalgae.

Thermokarst

Thermokast features are small depressions formed by the degradation of permafrost form a common feature in the midst of cryoplanation platforms (Figure S1l). In general, they are disconnected from the drainage, although some present-day lakes may have their genesis associated with the lateral expansion of the Termokarst.

Deposit features

These consist of the movement of material within the active layer as a result of the action of freezing/thawing (Figure S1m). These are chaotic

structures formed from materials of different sizes and strength as a result of the freezing and thawing of the ground.

Moraines are large lateral and frontal moraines originating from the Rotch Dome glacier and some sparse features in the interior of the peninsula (Figure S1o), derived from glacier advances and retreats from the Rotch Dome or from small cirque glaciers in the Holocene. These features occur on the eastern edge in the form of moraine ridges. Some show a sub-recent paraglacial origin, indicating the current climatic instability of the area.

Moraines colonized by vegetation are found in a small area on the north beach, near the front moraine of the Domo Rotch glacier. It is made up of several blocks of different sizes, mostly made of basaltic material, but there are some erratic ones, mainly made of granite. All of them are covered in crustose lichens.

Bottom moraines are ridges or deposits of rock fragments transported by an active glacier as a result of the melting of the base of the glacier (Figure S1p). One of the best-known forms is the mantos de till, also known as morainas de fundo. They cover large areas of the peninsula. Their topography is irregular with rock outcrops and small hills. These deposits alternate glacial and fluvio-glacial influence (advance and retreat). The thickness and type of material can indicate the climatic dynamics imposed on the region and provide input for geological studies. In Byers, the coarser material deposited has been intensively worked by glacial and periglacial processes over the last 10,000 years of glacier retreat.

At higher altitudes above 80m, the harsh climatic conditions and heavy snow cover in winter have led to the development of large *cryoplaned surfaces* with little vegetation cover, similar to the Polar Desert (Figure S1q).

Soil database analysis in Byers Peninsula

To evaluate this dataset, a principal component analysis (PCA) was conducted using the first three dimensions, which together account for 76.60% of the cumulative variance (Figure 3). The first PCA, comprising Dim1 and Dim2, explains 64.43% of the total variance in the data (Figure 3a). The variables that most explain Dim1 are pH, Ca, Mg, and E-CEC, whereas for Dim2, the most explanatory variables are Sandy, Clay, and H + Al. Geological groups exhibit significant overlap, not separating completely. However, it is observed that clay content tends to dominate the formation of Marine Mudstones, which, incidentally, show the highest levels of this variable.

Profiles developed on the formation of Sills are highly diverse, with several variables contributing to their explanation, such as OC, Ca, Mg, and E-CEC, a fact evidenced and explained by the different soil classes included in this formation. Finally, the Quaternary Beach Gravels formation is highlighted by the influence of Sand, showing the highest values for this variable. In this same PCA, it is possible to observe that pH,

Na, Ca, Mg, CEC-E are negatively correlated with P, and H + Al.

The PCA derived from Dim1 and Dim3 explains 53.8% of the total variance in the data (Figure 3b). The variables that most contribute to Dim3 are Na, P, and OC. An interesting point is that clay content is negatively correlated with the levels of P and H+Al. In addition, as observed in the first PCA, the groups tend to overlap, with many intersections, explaining that geology is not a factor that conditions the separation of the groups. Again, the Sills formation is widely distributed among the variables. The Intrusive Basalt formation appears with some individuals correlating with the levels of Sand and P. On the other hand, the Breccias formation tends to be closer to pH values.

DISCUSSION

The Byers Peninsula is of high geological-biological value because it contains the most complete record of the Jurassic-Early Cretaceous period in the northern Pacific flank of the magmatic arc complex (Bastias et al. 2020).

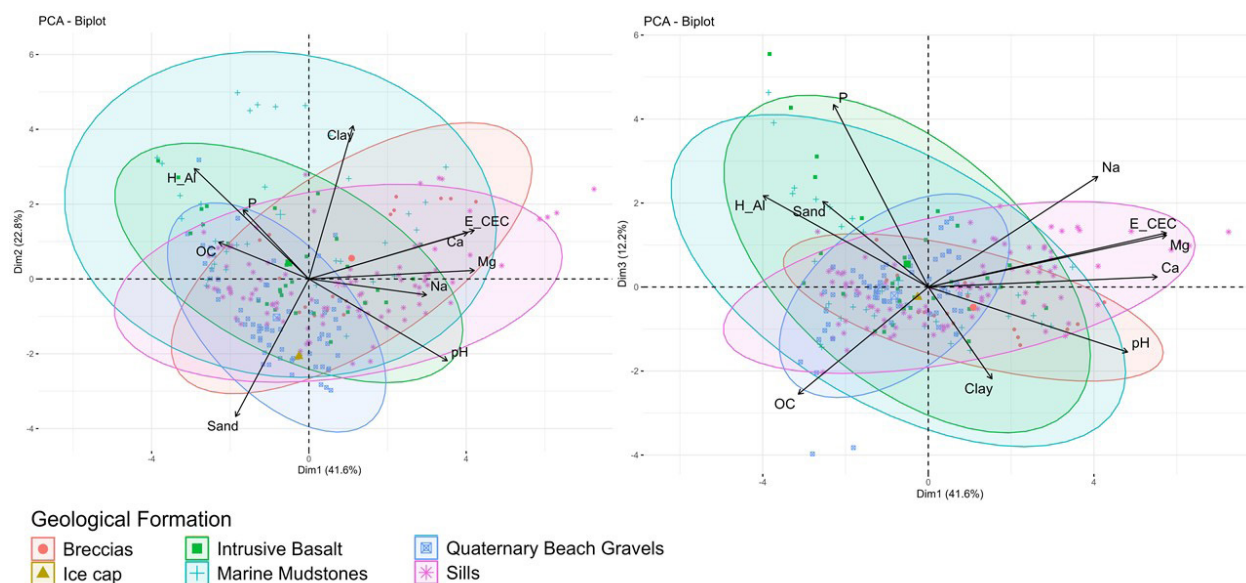


Figure 3. Principal component analysis performed. The first (a) comprises Dim1 and Dim2, and the second (b) Dim1 and Dim3.

The oldest geological units are associated with deep marine sedimentary rocks, with volcanic rocks also present in the Start Hill Formation, the slope-apron sandstones of the President Beaches Formation, and marine conglomerates and argillites in the Chester Cone Formation. (Bastias et al. 2020).

Based on the PCA data, the geology of Byers is not an exclusive conditioning factor for the soil characteristics evaluated, do not limit or separate the soil classes that develop on them, showing that the different soil classes identified can develop on both geologies. As illustrated in Table I and based on the lithologies of origin for each described profile, various soil classes, including ornithogenic and non-ornithogenic soils, are found in the area, not following a pattern of occurrence directly linked to the geology.

According to Simas et al. (2008), due to the incipient conditions of chemical weathering, the soils of Maritime Antarctica are directly correlated with the parent material. However, Moura et al. (2012) also found soils with different classes and chemical characteristics situated on the same parent material. What most limits the development of these soils on both geologies are the local conditions and their position in the landscape, which will reflect on the intensity of the pedogenetic processes at work, as well as the colonization of these areas by both plant and animal organisms.

The characteristics of ornithogenic soils contributed to the negative correlation observed in both PCAs. These soils stand out due to their distinct chemical properties, including low pH, high phosphorus concentration, elevated aluminum activity, and variations in calcium, magnesium, and potassium levels in the exchange complex (Simas et al. 2007).

The interior of the Byers Peninsula is dominated by a series of extensive platforms at

altitudes of up to 105 m, interrupted by isolated volcanic plugs such as Chester Cone (188 m.a.s.l.) and Negro Hill (143 m.a.s.l.). There is an abundance of rounded, flat landforms resulting from marine, glacial and periglacial erosional processes. The most rugged terrain occurs on Ray Promontory, a ridge forming the northwest-trending axis of the roughly 'Y'-shaped peninsula. Precipitous cliffs surround the coastline at the northern end of Ray Promontory with Start Hill (265 m) at the NW extremity being the highest point on the peninsula.

The ancient retreat of the Rotch glacier on the Byers Peninsula favored the action of geomorphological agents, creating the greatest variety of periglacial geoforms in Maritime Antarctica. Interaction with the biota also allowed pedogenesis to advance, with ornithogenic soils showing greater pedogenetic development, exhibiting greater depths, higher P contents and OC accumulations. The glacioisostatic uplift of the marine terraces leads to the migration of elephant seals, penguins, petrels and other birds, spreading and intensifying the nesting effect in these soils.

Periglacial erosion is responsible for redistributing and mixing a large part of the rock's physical weathering products, obliterating the geological contacts in smoother but sharper reliefs. The retreat of the glacier on the peninsula is associated with the Holocene retreat 8.3-5.9 B.P. ago (Oliva et al. 2016, Toro et al. 2013). The relief ranges from 0 to 270 m above sea level (m.a.s.l.), and pre-Holocene surfaces between 80 and 250 m.a.s.l. on the Byers Peninsula show clear evidence of glacial relief. Marine, glacial and periglacial erosional processes form a generally low and gentle relief. Ten levels of raised beaches, at elevations between 2 and 84 m.a.s.l., expose marine sedimentary materials. Low platforms between 50 and 70 m.a.s.l. occur on Cretaceous clastic sedimentary rocks. A

cryoplanar surface, developed on volcanic tuffs, is the upper platform, above 70 m.a.s.l. Cliffs and isolated hills of Juro-Cretaceous volcanic and volcanoclastic rocks occur between 140 and 265 m.a.s.l. Shallow and loam Cryosols, Leptosols, and Regosols are the main soil groups in Byers Peninsula (Moura et al. 2012, Navas et al. 2006, 2008).

The identification, description and mapping of the various periglacial landforms observed are important tasks for a better understanding of the pedogenic dynamics at work in a given area, especially when it comes to a region in Maritime Antarctica. The presence of these landforms provides some insight into the processes that have been and continue to be involved in the development of local soils.

CONCLUSIONS

1. There is a close interplay between soil groups and lithological and geomorphological features in Byers Peninsula.

2. The integrated study of all soils collected in this peninsula showed that more stable soils, where periglacial erosion is less, such as upper cryoplanation platforms, raised beaches, volcanic plugs and areas under ornothogenic influences, have soils with a higher degree of development and weathering degrees. On the other hand, very dynamic periglacial landforms, like scree stony slopes and talus, have low soil development, and unstable landscapes.

3. Byers Peninsula is one of the most pedodiverse areas in Maritime Antarctica, due to varying lithologies, landforms and widespread ornothogenic influence by different seabirds, and long-term vegetation establishment.

4. The Byers Peninsula is an example of the complex interactions between periglacial processes and soil development, making it

an important site for our understanding of polar geomorphology. The comprehensive characterization of soil profiles and their interactions with landforms and lithology not only reveals the complexity of soil formation in extreme environments but also provides critical insights into the resilience and adaptability of these systems under changing climatic conditions. This study underscores the importance of preserving such unique landscapes for ongoing scientific research and environmental monitoring.

Acknowledgments

We thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) for financial support. We are grateful to INCT da Criosfera, TERRANTAR and MARINHA DO BRASIL (PROANTAR PROGRAM) for financial support and field assistance.

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How to cite

SILVA JP, FRANCELINO MR, FARIA ALL, PALMA HP, OLIVEIRA IA, SOUZA JJLL & SCHAEFER CEGR. 2024. Soils from Byers Peninsula, Maritime Antarctic: landform-lithology controls in soil formation. *An Acad Bras Cienc* 96: e20240583. DOI

*Manuscript received on June 5, 2024;
accepted for publication on November 1, 2024*

JÔNATAS PEDRO DA SILVA¹

<https://orcid.org/0000-0001-5114-8329>

MÁRCIO R. FRANCELINO¹

<https://orcid.org/0000-0001-8837-1372>

ANDRÉ LUIZ L. DE FARIA²

<https://orcid.org/0000-0003-0492-9725>

HEITOR P. PALMA¹

<https://orcid.org/0009-0006-2428-365X>

ISABELLE DE A. OLIVEIRA¹

<https://orcid.org/0009-0006-7627-5934>

JOSÉ JOÃO L.L. DE SOUZA¹

<https://orcid.org/0000-0003-4670-6626>

CARLOS ERNESTO G.R. SCHAEFER¹

<https://orcid.org/0000-0001-7060-1598>

¹Universidade Federal de Viçosa - UFV, Departamento de Solos, Av. Peter Henry Rolfs, s/nº, Campus Universitário Viçosa, 36570-900 Viçosa, MG, Brazil

²Universidade Federal de Viçosa - UFV, Departamento de Geografia, Av. Peter Henry Rolfs, s/nº, Campus Universitário Viçosa, 36570-900 Viçosa, MG, Brazil

Correspondence to: **Jônatas Pedro da Silva**

E-mail: jpedro.agronomo@gmail.com



SUPPLEMENTARY MATERIAL

Figures S1, S2.

Table S1.