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SOIL FORMATION, DISTRIBUTION, AND VEGETATION INTERPLAYS AT LIONS RUMP, MARITIME ANTARCTICA

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ABSTRACT

The objective was to study soil formation and to analyze the relationships between soil distribution and vegetation cover at Lions Rump, King George Island, Maritime Antarctica. WRB and Soil Taxonomy systems were applied in association with geomorphological features. Thirteen pedons were sampled and described for their physical, chemical, and mineralogical attributes. Soil mapping and vegetation distribution were performed. Results showed that soils are mainly formed from weathered basalt-andesitic rocks, which are naturally rich in apatite, and have a high P background. Typic Dystrogelepts ornithic and Typic Gelorthents ornithic are the main ornithogenic soils in the study area. Typic Dystrogelepts ornithic represent the deepest, most structured, and reddish soils at Lions Rump. Typic Haplogelepts ornithic are the main soils on the first and second moraine levels from White Eagle Glacier. Typic Haploturbels and Lithic Haploturbels are present just above 80 m a.s.l. (above sea level), especially on the top areas and paraglacial spots, with gelic materials within 100 cm of the soil surface and permafrost within 200 cm. Despite occurring only at higher altitudes, they represent the most extensive soil cover at Lions Rump. Turbic Haplogelepts and Typic Haplorthents occur between 40 and 80 m a.s.l., without the influence of bird nesting and with permafrost absent to a depth of 200 cm. Vitrandic

Cryopsamments and Oxyaquic Cryopsamments dominated the first level of terraces and former beaches along the coastal area. Other soils, classified as Lithic Cryorthents Ornithic and Typic Gelifluvents ornithic, occur in very restricted areas: the former on sea stack rock outcrops (basaltic plugs) near the beach, and the latter in a small portion of glacial alluvial fans. Overall, soil distribution and classification in Lions Rump allowed the identification of two main soil domains: Ornithogenic soils (without permafrost) and the Gelisols (above 80 m a.s.l.). Higher P and N contents at ornithogenic sites favor vegetation establishment with the presence of *Deschampsia antarctica* and *Colobanthus quitensis*.

Keywords: Cryoturbation; Edaphic processes; Mapping; Ornithogenic soils; Vegetation cover.

RESUMO

FORMAÇÃO DO SOLO, DISTRIBUIÇÃO E INTER-RELAÇÕES COM A VEGETAÇÃO EM LIONS RUMP, ANTÁRTICA MARÍTIMA. O objetivo foi estudar a formação do solo, e buscar relações entre a distribuição edáfica e a cobertura vegetal em Lions Rump, Ilha Rei George, Antártica Marítima. Os sistemas WRB e Soil Taxonomy foram aplicados em associação com as características geomorfológicas. Treze perfis de solo foram amostrados e descritos quanto aos atributos físicos, químicos e mineralógicos. O mapeamento do solo e a distribuição da vegetação foram realizados. Os resultados mostraram que os solos são formados principalmente por rochas basálticas-andesíticas intemperizadas, naturalmente ricas em apatita, com alto teor de fósforo. Os solos ornitogênicos Typic Dystrogelepts ornithic e Typic Gelorthents ornithic são os principais na área de estudo. O Typic Dystrogelepts ornithic representa os solos mais profundos, estruturados e avermelhados em Lions Rump. O Typic Haplogelepts ornithic é o principal solo nos primeiros e segundos níveis de morainas da Geleira White Eagle. Os Typic Haploturbels e Lithic Haploturbels estão presentes logo acima de 80 m de altitude (acima do nível do mar), especialmente nas áreas superiores e em pontos paraglaciais, com materiais gélicos a menos de 100 cm e permafrost a menos de 200 cm da superfície do solo. Apesar de ocorrerem apenas em altitudes mais elevadas, representam a maior cobertura de solo em Lions Rump. Os Haplogelepts Turbic e os Haplorthents Typic situam-se entre 40 e 80 m acima do nível do mar, sem influência de nidificação de aves e sem permafrost a menos de 200 cm de profundidade. Os Cryopsamments Vitrandic e os Cryopsamments Oxyaquic dominaram o primeiro nível dos terraços e antigas praias ao longo da zona costeira. Outros solos classificados estão presentes em áreas muito limitadas: os Cryorthents Lithic ornithic nos afloramentos rochosos dos pilares marinhos (plugues basálticos) perto da praia, e os Gelifluvents Typic ornithic, numa pequena área nos leques aluviais glaciais. De forma geral, a distribuição e a classificação do solo em Lions Rump permitiram identificar dois domínios principais de solo: solos ornitogênicos (sem permafrost) e Gelissolos (acima de 80 m de altitude). Os maiores teores de P e N em locais ornitogênicos favorecem o estabelecimento da vegetação com a presença de *Deschampsia antarctica* e *Colobanthus quitensis*.

Palavras-chave: Cobertura vegetal; Crioturbação; Mapeamento; Processos edáficos; Solos ornitogênicos.

RESUMEN

FORMACIÓN DEL SUELO, DISTRIBUCIÓN E INTERRELACIONES CON LA VEGETACIÓN EN LIONS RUMP, ANTÁRTIDA MARÍTIMA. El objetivo de este estudio fue investigar la formación del suelo y evaluar las relaciones entre la distribución edáfica y la cobertura vegetal en Lions Rump, Isla Rey Jorge, Antártida Marítima. Se aplicaron los sistemas WRB y Soil Taxonomy en asociación con características geomorfológicas. Se muestrearon trece perfiles de suelo, descritos en términos de sus atributos físicos, químicos y mineralógicos. Se realizó la cartografía de suelos y se analizó la distribución de la vegetación. Los resultados mostraron que los suelos están formados principalmente por rocas basáltico-andesíticas meteorizadas, naturalmente ricas en apatita y con alto contenido de fósforo. Los suelos ornitogénicos Typic Dystrogelepts (ornithic) y Typic Gelorthents (ornithic) predominan en el área de estudio. El Typic Dystrogelepts (ornithic) representa los suelos más profundos, estructurados y de tonalidad rojiza de Lions Rump. El Typic Haplogelepts (ornithic) es el suelo principal en el primer y segundo nivel de morrenas del glaciar White Eagle. Los Typic Haploturbels y Lithic Haploturbels se presentan justo por encima de los 80 m de altitud, especialmente en las zonas superiores y en puntos paraglaciares, con materiales gélidos a menos de 100 cm y permafrost a menos de 200 cm de la superficie del suelo. Aunque restringidos a las mayores altitudes, representan la mayor cobertura edáfica en Lions Rump. Los Turbic Haplogelepts y Typic Haplorthents se localizan entre 40 y 80 m s.n.m., sin influencia de anidación de aves y sin permafrost a menos de 200 cm de profundidad. Los Vitrandic Cryopsamments y Oxyaquic Cryopsamments dominan el primer nivel de terrazas y antiguas playas de la zona costera. Otros suelos clasificados ocurren en áreas muy limitadas: Lithic Cryorthents (ornithic) en los afloramientos rocosos de los pilares marinos (tapones basálticos) próximos a la playa, y Typic Gelifluvents (ornithic) en un área reducida de abanicos aluviales glaciares. En conjunto, la distribución y clasificación de los suelos en Lions Rump permitió identificar dos dominios edáficos principales: suelos ornitogénicos (sin permafrost) y Gelisoles (por encima de los 80 m de altitud). Las mayores concentraciones de P y N en los ambientes ornitogénicos favorecen el establecimiento de la vegetación, especialmente de *Deschampsia antarctica* y *Colobanthus quitensis*.

Palabras clave: Cobertura vegetal; Crioturbación; Cartografía; Procesos edáficos; Suelos ornitogénicos.

1 INTRODUCTION

Soil formation in Antarctica is restricted to about 0.32% or 45.000 km^2 of the continent, in ice-free coastal regions and glacial valleys between mountain ranges (Ugolini and Bockheim, 2008). The first study of Antarctica soils was conducted at McMurdo US Base by Jensen in 1916, and the first field study and soil mapping compilation were conducted in the Taylor Valley, southern Victoria Land, by McCraw in 1967 (Ugolini and Bockheim, 2008). Despite increased research on soils in recent years, most studies on Maritime Antarctica focused mainly on Ornithogenic soils (Daher et al., 2019; Michel et al., 2006; Pereira et al., 2013; Rodrigues et al., 2021; Sacramento et al., 2023; Schmitz et al., 2024; Simas et al., 2007).

Although the temperatures are very low in the Antarctic, chemical weathering occurs (Mello et al., 2023). Some studies have shown that chemical weathering in Gelisols occurs to a greater extent than previously thought (Blume et al., 2002; Lopes et al., 2022b; Pereira et al., 2013; Schaefer et al., 2008; Simas et al., 2006; Siqueira et al., 2021). Ugolini and Bockheim (2008) observed that Antarctic soils with ice-cemented permafrost within 70 cm of the surface are generally cryoturbated and classified in the Turbel suborder. In contrast, soils with dry permafrost and minimal cryoturbation are classified as Orthels. Soils in coastal regions of Antarctica are in Haplo great group, and soils further inland in areas receiving less than 50 mm of water-equivalent precipitation are in Anhy great group. Antarctica soils are further differentiated at the subgroup level based upon the amount and type of salts and other diagnostic features (Ugolini & Bockheim, 2008).

One characteristic of Gelisols is very low clay content, which even in the oldest soils from Continental Antarctica seldom exceed 4% (Beyer et al., 1999). Moreover, in the Maritime Antarctic, clay content can reach 20%, surpassing that of continental areas and indicating advanced weathering in this region. In general, in Continental Antarctica, the youngest soils are found in coastal regions and lower valleys, and the oldest ones at higher altitudes inland (Beyer et al., 1999). However, in the Maritime Antarctic, more developed soils are found near the ocean, especially in ornithogenic soils (Almeida et al., 2021).

In the Maritime Antarctic, the mean annual temperature is considerably higher (-1 ºC to -3 °C) than in the continental area. The mean annual precipitation is 400 to 500 mm (Bockheim & Ugolini, 1990). Under these climatic conditions, vegetation cover becomes more extensive, featuring a rich diversity of mosses and lichens, along with two native angiosperm species found in Antarctica, the Poaceae *Deschampsia antarctica* Desv. and the Caryophyllaceae *Colobanthus quitensis* (Kunth) Bartl. (Schmitz et al., 2020).

In the peripheral regions of Antarctica, the expansion of ice-free areas and ongoing soil formation processes have been increasingly observed (Moura et al., 2012), underscoring the need for detailed studies to support conservation initiatives, particularly within Antarctic Specially Protected Areas (ASPAs). Accordingly, soil maps are fundamental tools for environmental management, planning human activities, and advancing ecological research in terrestrial ecosystems.

Several soil studies and mapping efforts have been conducted in Maritime Antarctica by the Terrantar research group (e.g. Francelino et al., 2011; Cazaroto et al., 2025; Lopes et al., 2022a; Meier et al., 2022; Mello et al., 2023; Michel et al., 2014; Moura et al., 2012; Poelking et al., 2015; Rodrigues et al., 2019; Sacramento et al., 2023; Schaefer et al., 2015; Schmitz et al., 2024; Silva et al., 2024; Siqueira et al., 2021). These studies have produced geomorphological and soil maps for ice-free areas in the South Shetland Archipelago and the Antarctic Peninsula, aiming to support ANTPAS (Antarctic Permafrost, Soils and Periglacial Environments) projects, expand scientific knowledge of the region, monitor the current state of Antarctic soils, and provide a basis for ecological research and conservation strategies. However, despite these efforts, there remains a need for more detailed local-scale studies linking soil characteristics with vegetation patterns in specific ice-free environments. This study aims to characterize the main soil classes at Lions Rump, King George Island (Maritime Antarctica), relate their chemical, physical, and mineralogical properties to vegetation patterns, and produce a detailed soil map of the area.

2 MATERIAL AND METHODS

2.1 Study area

Lions Rump is a small peninsula located on the southern coast of King George Bay, King George Island, in the South Shetland Archipelago, Maritime Antarctica (Figure 1). The area is designated as an Antarctic Specially Protected Area - ASPA nº 151 (Antarctic Treaty Consultative Meeting [ATCM], 2024) and takes its name, Lions Rump, from the distinctive rocky hill lying between the southern extremity of King George Bay and Lions Cove. According to Köppen's classification, the region is characterized by a tundra climate (ET). Meteorological data from the nearby Brazilian Antarctic research station Comandante Ferraz, located near Lions Rump, indicate mean air temperatures ranging from -6.4 °C in July to 2.3 °C in February. Mean annual precipitation is approximately 400 mm (Simas et al., 2007). However, the actual soil water regime is strongly influenced by topography, as intense melting of snow, glaciers, and permafrost sites upstream during the summer (Almeida et al., 2014). Temperatures remain above freezing for most of the summer (November to March), allowing the vigorous growth of plant communities, mainly mosses, lichens, and algae (Schaefer et al., 2004b). The area includes the littoral and sublittoral zones extending from the eastern end of Lajkonik Rock to the northernmost point of Twin Pinnacles. From this point, the boundary extends to the easternmost end of the columnar plug of Lions Head, east of White Eagle Glacier (Scientific Committee on Antarctic Research [SCAR], 2002). On land, the area encompasses raised beaches, freshwater pools, and streams on the south side of King George Bay, around Lions Cove, and the moraines and slopes that lead to the lower ice tongue of White Eagle Glacier, continuing westward to a small moraine that protrudes through the ice cap southeast of Sukiennice Hills.

The geology of Lions Rump consists of Paleogene lavas and tuffs containing thin brown coal intercalations, petrified wood fragments, and

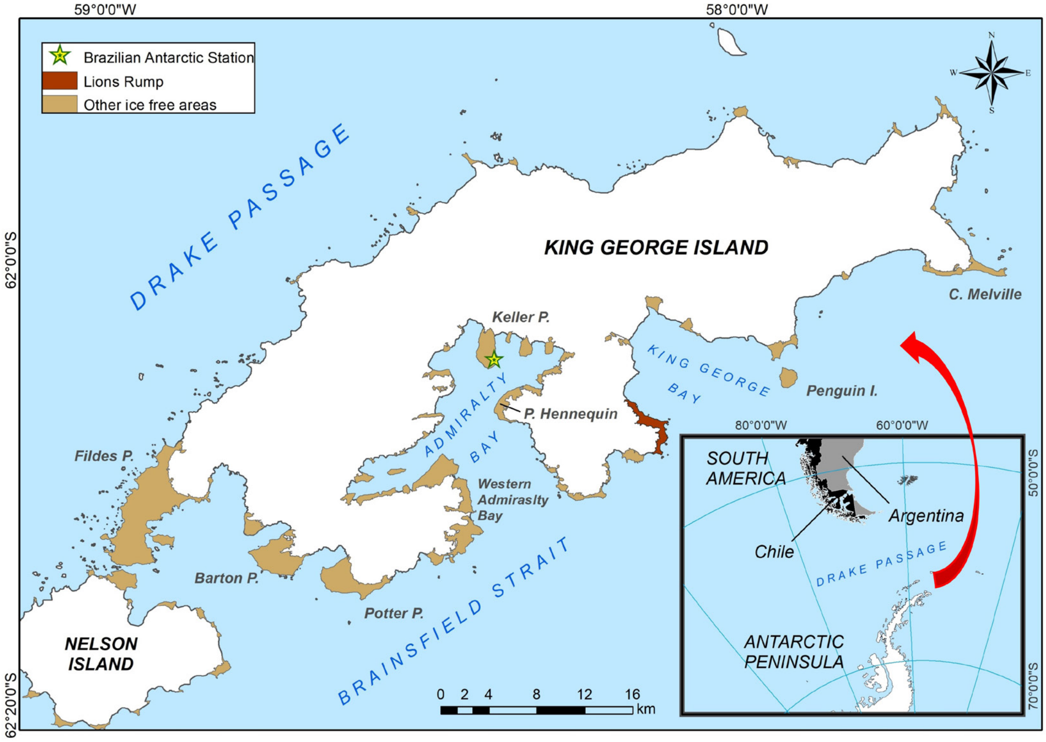

FIGURE 1 – Lions Rump located at King George Bay, King George Island, Maritime Antarctica.

Quaternary deposits. The front of White Eagle Glacier is marked by large, dome-shaped moraine ridges that correspond to several Holocene stages of glacier advance and retreat (Birkenmajer, 1994a, 1994b; SCAR, 2002).

Two Paleogene lithostratigraphic groups have been described, separated by a major fault: the Polonia Glacier Group, composed of volcanic and volcanoclastic rocks of Eocene age in the north; and the Chopin Ridge Group, comprising Upper Cretaceous and Oligocene volcanic rocks and Lower Oligocene glacial and glaciomarine deposits in the south. Both groups include several formations and members (Birkenmajer, 1994a).

The Quaternary deposits consist of three generations of moraines, outwash plains, shorelines, and raised beach deposits. The first generation of moraines formed during glacier advances in the second half of the 18th century; the second developed prior to 1960; and the third between 1988 and 1991 (Angiel & Dąbski, 2012; ATCM, 2024).

The first generation of marginal (lateral) moraines occurs on both sides of the valley of the northeastern flank of White Eagle Glacier, terminating at marine abrasion cliffs and bordered by recent pebble dikes up to 3.5 m high. The second generation is represented by an isolated crescent-shaped ridge that extends down to the seashore at King George Bay and is overlain by younger moraines at its landward end. The late and youngest generations form several ridges along the margin of White Eagle Glacier, which descend steeply toward Lions Cove and King George Bay, covering the recent beach. An outwash apron is currently being formed at the outlet of a glacial stream that has incised a deep canyon into the recent moraines, and smaller outwash cones are present on both sides of the older moraine ridge (Birkenmajer, 1981; Birkenmajer, 1994b).

Along the shoreline, pebbly storm ridges have developed, enclosing small lagoons. Traces of raised beaches with well-rounded pebbles are visible at 15 to 20 m a.s.l. on a morphological ridge separating Lions Cove from King George Bay (Birkenmajer, 1981).

The ice-free area exhibits a variety of geomorphological features, including beaches of varying width and length, moraines, hills, and inland rock outcrops.

2.2 Soil collection

A total of 13 pedons representing the main soil types identified in ice-free areas of Lions

Rump were described and sampled, following the criteria established by Antarctic and Sub-Antarctic Permafrost, Soils and Periglacial Environments Group (Antarctic Permafrost and Soils, [ANTPAS], 2006) (Table 1). Soil classification followed the Soil Taxonomy (Soil Survey Staff, 2010) and the World Reference Base for Soil Resources (IUSS Working Group [WRB], 2015). For detailed soil mapping, the free-choice profiling was applied (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 1995). The cartographic base consisted of a Quickbird image scale of 1:4,500). Data processing and map editing were performed using ArcGIS 9.3 software (Environmental Systems Research Institute, Inc. [ESRI], 2009).

2.3 Vegetation identification and fauna activity

The vegetation surrounding the profile was collected and identified. Moss species were identified using the taxonomic keys of Ochyra (1998), Ochyra et al. (2008), Putzke and Pereira (2001), whereas lichen species were identified using the keys of Olech (2004), Øvstedal and Lewis-Smith (2001), and Redón (1985). Faunal activity was evaluated by observing the animals inhabiting the site at the time traces were collected (nests, bones, guano).

2.4 Chemical, physical, and mineralogical analyses

Physical analyses were performed according to Ruiz (2005). The soil chemical attributes determined included pH (in H_2O and 1 mol L^{-1} KCl), total organic carbon (TOC) in extracts of fulvic acid, humic acid and humin fractions (Yeomans and Bremner, 1988); available P, Na and K after extraction with 0.5 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4 (Mehlich-1); Ca, Mg, and Al after extraction with 1 mol L^{-1} KCl; exchangeable acidity ($H^+ + Al^{3+}$) after extraction with 0.5 mol L^{-1} $Ca(CH_3COO)_2$ at pH 7.0; and $CaCO_3$ by titration following extraction with 0.5 mol L^{-1} HCl. All chemical analyses were conducted according to Embrapa (2017). Samples were also analyzed for total element contents (Ca, Mg, K, Fe, Al, Mn, P, Cu, Zn, Cd, As, Cr, and Pb) after total digestion of sieved material (< 0.25 mm) using HCl, HNO_3 and HF, by heating in a microwave digestion system (CEM MDS - 2000), following the EPA-3052

TABLE 1 – Geographic distribution, vegetation cover, and soil classification of pedons

Pedon	*Geographic position*[1]	*Altitude m.a.s.l*[2]	*Vegetation*[3]	*WRB*[4]	*Soil Taxonomy*
LR3*	0439687; 3110784	62	Rare D.C.L.M	Haplic Cambisol (Eutric, Skeletic, Turbic, Gelic)	Loamy-skeletal, mixed, active, subgelic, Turbic Haplogelepts
LR4*	0439762; 3110565	102	Rare D.C.L.M	Turbic Cambic Cryosol (Eutric, Skeletic)	Loamy-skeletal, mixed, active, subgelic, Typic Haplorthels
LR5*	0440047; 3110231	110	Absent	Haplic Regosol (Eutric, Skeletic, Gelic)	Loamy-skeletal, mixed, active, subgelic, Typic Gelorthents
LR12*	0440724; 3108658	257	L>D>C>M	Leptic Cryosol (Eutric, Skeletic)	Loamy-skeletal, mixed, active, subgelic, Lithic Haploturbels
LR13*	0440804; 3108792	222	Absent	Turbic Thionic Cryosol (Epieutric, Endoalumic, Skeletic)	Loamy-skeletal, mixed, active, subgelic, Typic Haplorthels
LR19*	0440081; 3110799	3	D>M>C	Haplic Arenosol (Eutric, Gelic)	Sandy, mixed, active, subgelic, Oxyaquic Cryopsamments
LR21*	0441211; 3109813	67	M>D >C	Haplic Cambisol (Eutric,Turbic, Gelic, Oxyaquic)	Coarse-loamy, mixed, active, subgelic, Turbic Haplogelepts
LR24*	0441165; 3109959	86	L>D>C>M	Turbic Cambic Cryosol (Eutric, Skeletic)	Sandy-skeletal, mixed, active, subgelic, Typic Haploturbels
LR8**	0441398; 3110372	38	D>M>P>L	Haplic Cambisol (Ornithic. Dystric. Skeletic, Gelic)	Loamy-skeletal, mixed, active, subgelic, Typic Dystrogelepts ornithic
LR9**	0441523; 3110476	40	P>D>L	Haplic Leptosol (Ornithic, Dystric, Skeletic, Gelic)	Loamy-skeletal, mixed, active, subgelic, Typic Gelorthents ornithic
LR15***	0441154; 3110281	41	D>C>L>P	Haplic Cambisol (Ornithic,Eutric, Gelic)	Coarse-loamy, mixed, active, subgelic, Typic Haplogelepts ornithic
LR22***	0439889; 3111016	4	L	Lithic Leptosol (Ornithic, Eutric)	Sandy-skeletal, mixed, active, subgelic, Lithic Cryorthents ornithic
LR23***	0441054; 3110247	17	P >D	Colluvic Regosol (Ornithic, Eutric, Gelic)	Sandy-skeletal, mixed, active, subgelic, Typic Gelifluvents ornithic

[1]UTM coordinates, zone 21S datum WGS 84; [2] Meters above sea level; [3] C= *Colobanthus quitensis.* D= *Deschampsia antarctica.* M= Mosses, L= Lichens, P = *Plasiola crispa*; [4] Classification following World Reference Base for Soil Resources (2006). *Non-ornithogenic soil; **Acid pH ornithogenic soil; ***Neutral pH ornithogenic soil.

method (United States – Environmental Protection Agency [US-EPA], 1996). Element concentrations were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES). The mineralogical composition of the clay fraction was evaluated on air-dried samples using X-ray diffraction (XRD) on both natural clay and clay samples after saturation with 1.0 mol L^{-1} KCl; heating at 350 ºC and 550 °C for 3 hours each; and saturation with 1.0 mol L^{-1} $MgCl_2$ followed by glycerol solvation. XRD analyses were performed using an X'Pert Pro diffractometer operating at 40 kV and 30 mA with CoKα radiation, within the range of 4-50 °2θ, at a step of 0.017 °2θ and a scan rate of 1 step s^{-1}.

3 RESULTS AND DISCUSSION

3.1 General characterization of the study area

Several species of flora and fauna were observed at Lions Rump. Due to the extensive ice-free areas that form an environmental gradient, the region provides shelter and suitable nesting sites. Consequently, birds and marine mammals establish large colonies of penguins, sea lions, and elephant seals, which over the years contribute significant inputs of marine-derived nutrients to the terrestrial ecosystem (ATCM, 2024; Tatur, 1989). In this way, they influence pedogenetic processes and promote vegetation development.

In the sampled area, 23 species of lichens, 10 species of mosses, the two native angiosperm species *Deschampsia antarctica* and *Colobanthus quitensis*, and the terrestrial macroscopic alga *Prasiola crispa* were identified. When present, vegetation cover varied markedly among profiles, differing in composition and abundance according to local environmental conditions. The main vegetation cover, geographic location, and soil classification (WRB and Soil Taxonomy) for each profile are presented in Table 1. Overall, the soils at Lions Rump are incipient and poorly developed. Some profiles located adjacent to active or abandoned penguin colonies (to be confirmed) were classified as ornithogenic soils. Cryosols/Gelisols were found in the highest portions of the landscape, whereas Cambisols/Inceptisols and Regosols-Arenosols-Leptosols/Entisols were widespread in the lowland areas.

According to the degree of ornithogenic influence, the soils were grouped as follows: Non-ornithogenic soils (LR3, LR4, LR5, LR12, LR13, LR19, LR21, LR24); Acid pH ornithogenic soils (LR8, LR9); and Neutral pH ornithogenic soils (LR15, LR22, LR23) (Table 1; Figure 2).

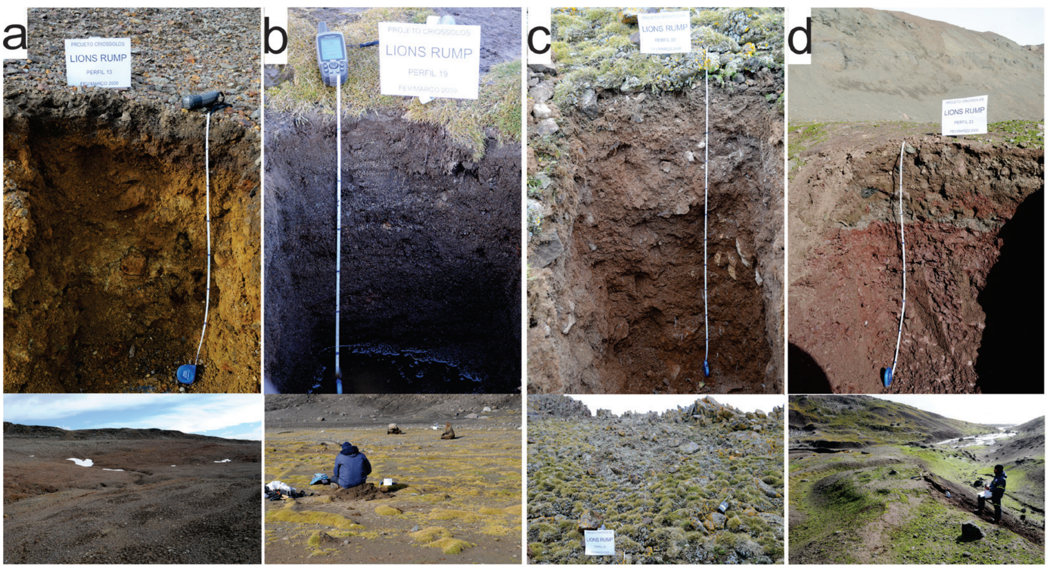

FIGURE 2 – Representative soil profiles for each group and their corresponding landscapes at Lions Rump: (a) Non-ornithogenic soil without vegetation cover (profile LR13); (b) Non-ornithogenic soil predominantly covered by *Deschampsia antarctica* (profile LR19); (c) Ornithogenic soil with acidic pH and vigorous vegetation cover (profile LR8); (d) Ornithogenic soil with neutral pH (profile LR23).

3.2 Vegetation

Lichens are widespread on rock fragments across all soil orders present in the study area. The lichen species observed at Lions Rump include *Acarospora sp, Bacidia sp, Buellia sp, Caloplaca cinericola*, *Caloplaca regalis*, *Candelaria flava*, *Cornicularia aculeate*, *Haematomma erytromma*, *Lecanora polytropa*, *Lecidea sp, Leptogium puberulum*, *Mastodia tesselata*, *Ochrolechia antarctica*, *Ochrolechia frigida*, *Physcia caesia*, *Placopsis contortuplicata*, *Psoroma cinnamomeum*, *Ramalina terebrata*, *Rhizocarpon geographicum*, *Rhizoplaca sp, Sphaerophorus globosus, Usnea antarctica*, *Usnea aurantiaco-atra* and *Xanthoria candelaria*. Some species, such as *Buellia sp., L. puberulum,* and *U. antarctica,* are also frequently observed covering vegetated soils. At higher elevations, soils are almost devoid of vegetation, except for sparse epilithic lichens. Above 80 m a.s.l., *Usnea* becomes the dominant lichen on Gelisols (Cryosols). As already reported for other areas of Maritime Antarctica, *Usnea* spp. are commonly found in exposed sites such as plateau areas, rocky slopes, moraines, and felsenmeers, which indicate a more stable, rocky, and well-drained landscape (Poelking et al., 2015; Schaefer et al., 2004a; Schmitz et al., 2021).

The moss species found at Lions Rump were *Andreaea gainii, Brachytecium sp, Bryum argenteum, Bryum dichotomum, Bryum pseudotriquetrum, Polytrichum alpinum, Sanionia uncinata, Schistidium falcatum,* and *Syntrichia princeps.* Mosses occur mainly in wet areas, positively associated with higher water content and waterlogging, forming carpets or cushions on various soil types (Schmitz et al., 2021). In wetter sites, cryptogamic organisms form a continuous cover, promoting the development of A horizons characterized by a sharp boundary with the underlying B horizon and decreasing organic C with depth. In the southern part of Lions Rump, extensive moss carpets, particularly those observed in pedon LR21, are undergoing degradation due to meltwater drainage.

Flowering plants are represented only by *Deschampsia antarctica* and *Colobanthus quitensis*, which occur primarily on Quaternary features, forming dense cover on uplifted terraces, beaches, moraines, and abandoned penguin rookeries. Water availability, along with wind exposure, substrate stability, and nitrogen availability, is considered a major factor influencing plant growth and distribution in the South Shetland Islands (Lindsay, 1971). This non-homogeneous spatial distribution of plants has also been reported on other islands in the South Shetland archipelago (Vera, 2011). Throughout the Maritime Antarctic, *D. antarctica* exhibits a much broader ecological amplitude than *C. quitensis* (Smith, 2003). At Lions Rump, both species occupy and cover extensive areas, but *D. antarctica* is notably more frequent.

The presence of *Prasiola crispa* is associated with the proximity of penguin rookeries, showing a clear preference for nitrogen-rich substrates and a high tolerance to the chemically harsh conditions created by guano enrichment, characterized by elevated concentrations of uric acid and nitrogen compounds (Kovačik & Pereira, 2001).

On the breeding rookery, all vegetation has been devastated due to excessive manuring and trampling by penguins, as previously reported by Michel et al. (2006), Simas et al. (2007), Tatur (1989), and Ugolini (1970, 1972) in their studies of ice-free areas of the South Shetland Archipelago. Only nitrophilous lichens are found on large stones and rocky walls. However, in marginal zones of penguin activity, the abundance of nutrients in meltwater draining from the rookery and dispersed by the wind supports the luxuriant development of vegetation. This pattern appears to be widespread across Maritime Antarctica, as documented by Michel et al. (2006), Schaefer et al. (2008), Simas et al. (2007, 2008), Tatur (2002), Tatur and Myrcha (1989, 1993), and Tatur et al. (1997). Long after the abandonment of penguin rookeries, the deposition of P- and N-rich guano favors the establishment of vegetation. These sites generally exhibit higher species diversity, greater vegetation cover, and the presence of ornithocoprophilous species (Ferrari et al., 2021).

3.3 Soil characteristics

Soil chemical properties, mineralogy and vegetation cover are strongly influenced by penguins, and soil drainage characteristics. Thus, we can divide soils from Lions Rump into three groups (Table 2): Acid pH ornithogenic soils (LR8, LR9), Neutral pH ornithogenic soils (LR15, LR22, LR23), and Non-ornithogenic soils (LR3, LR4, LR5, LR12, LR13, LR19, LR21, LR24).

The Acid pH ornithogenic soils are readily distinguished from the Non-ornithogenic soils by several features such as the presence of continuous vegetation cover with *D. antarctica, C. quitensis*, and/or *Prasiola crispa*; lower pH and bases

TABLE 2 – Morphological and physical properties of studied pedons

Pedon	*Horizon*	*Depth cm*	*Structure* [1]	*Transition*	*Color (dry)*	*Skel*[2]	*C.Sand*	*F. Sand*	*Silt*	*Clay*
						dag kg $^{-1}$				
Non-ornithogenic soils										
LR3	A	0-5	w f m bl/ md m gr	gradual wavy	2.5Y 4/3	22	29	21	36	14
	AB	5-17/20	w m bl/ md m gr	gradual wavy	2.5Y 4/4	25	27	20	33	20
	Bi	20-47/52	w m bl/ md m gr	gradual wavy	2.5Y 5/3	51	33	21	27	19
	BC	47-52-70	w m bl	–	2.5Y 5/4	55	31	18	32	19
LR4	A	0-5	w f bl/ md m gr	gradual wavy	2.5Y 5/2	35	46	16	28	10
	AB	5-22/24	w f m bl/ md m gr	gradual wavy	2.5Y 5/3	45	36	22	39	3
	Bi	24-45/47	md m l bl/ w m gr	gradual wavy	2.5Y 5/3	51	37	22	39	2
	BC	45/47-75	w md l bl	–	2.5Y 5/3	33	37	22	40	1
LR5	C1	0-23	w m bl/ w m gr	gradual wavy	2.5Y 4/3	36	28	14	56	2
	C2	23-60	w m bl/ w m gr	gradual wavy	2.5Y 4/4	27	33	11	53	3
	C3	60-90	w md l bl	–	2.5Y 5/4	32	34	11	53	2
LR12	A	0-8/25	st m gr	clear wavy	10YR 3/3	27	33	29	26	12
	C	8-25/30	md l sb/ st m gr	–	10YR 4/3	34	40	30	21	9
LR13	A	0-8	sg	clear flat	2.5YR 4/3	54	42	25	25	8
	AC	8-15	w md l sb/ w m gr	clear wavy	10YR 4/3	40	38	14	32	16
	C	15-65	w l sb/ w m gr	–	10YR 5.5/8	51	61	17	13	9
LR19	A	0-4	w l bl/ sg	clear wavy	2.5Y 3/3	1	54	21	15	10
	AC	4-12/15	w l bl/ sg	gradual wavy	2.5Y 4/4	17	65	11	2	22
	C1	15-30/35	sg	gradual wavy	2.5Y 4/3	23	82	6	5	7
	C2	30/35-70	sg	–	2.5Y 4/3	22	81	7	5	7
LR21	O	0-3/4	w l bl/ sg	clear wavy	10YR 3/4	26	23	25	40	12
	A	3/4-8/10	w l bl/ sg	gradual wavy	10YR 5/3	16	44	30	21	5
	AB	10-18/20	w m bl/ st m gr	gradual irregular	10YR 5/3	14	51	25	21	3
	Bi	20-45/50	md st l bl/ md m gr	gradual irregular	10YR 6/3	32	41	26	31	2
	BC	45/50-65	md m bl/ sg	–	10YR 6/3	30	38	27	33	2
LR24	A	0-8	w l bl/ sg	clear wavy	10YR 4/3	48	51	28	18	3
	AB	8-20	w l bl/ sg	gradual wavy	10YR 4/4	50	49	29	18	4
	BA	20-33	w m bl/ st m gr	gradual irregular	10YR 5/4	60	47	29	21	3
	Bi	33-52	md st l bl/ md m gr	gradual irregular	10YR 5/3	48	52	25	21	2
	BC	52-82	md m l bl	–	10YR 6/3	31	58	22	19	1
Acid pH ornithogenic soils										
LR8	O	0-5	fibric/ st m gr	clear flat	10YR 3/3	21	44	20	21	15
	A	5-12	w m l sb/ st m gr	clear flat	10YR 3/4	71	36	21	25	18
	AB	12-18	w m l sb/ st m gr	clear wavy	10YR 5/3	42	51	18	18	13
	BA	18-32	md f bl/ st m gr	clear wavy	10YR 6/3	55	57	11	21	11
	B1	32-70	md f bl/ st m gr	gradual wavy	10YR 6/3	45	52	23	16	9
	B2	70-100	st m gr	gradual wavy	10YR 6/4	42	40	33	20	7
	B3	100-120	st m gr	–	10YR 5/6	32	45	17	22	16
LR9	A	0-8	st m gr	gradual flat	10YR 5/3	49	43	23	21	13
	Cr	8-40	sg/ w m gr	–	10YR 7/3	67	30	8	39	23
Neutral pH ornithogenic soils										
LR15	O1	0-3/4	fibric	clear wavy	10YR 3/3	11	36	25	23	16
	O2	¾-9/11	fibric	clear wavy	10YR 3/4	0	36	25	23	16
	OA	11-16/17	fibric/ md m gr	gradual wavy	10YR 5/3	24	32	22	28	18
	Bi1	17-37/38	w md m l bl/ md m gr	gradual wavy	10YR 6/3	33	42	17	27	14
	Bi2	37/38-60	w m l bl/ w m gr	gradual irregular	10YR 6/3	27	43	17	25	15
	BC	60-80+	w m l bl	–	10YR 6/4	32	42	18	22	18
LR22	A	0-16	w l bl/ md m gr	abrupt irregular	5Y 2.5/2	48	81	10	4	5
LR23	A	0-8/10	w m l bl/ w m gr	clear wavy	10YR 4/2	25	54	19	22	5
	Bi	10-22/24	w m l bl/ md m gr	clear wavy	10YR 5/2	25	42	27	27	4
	C	24-28/30	w m bl/ md m gr	clear wavy	7.5YR 4/3	35	42	35	20	3
	2A	30-34/36	sg	clear wavy	7.5YR 4/2	59	65	23	11	1
	2C	34/36-90	st l bl/ md m gr	–	7.5YR 5/2	73	69	17	13	1

[1]Development: w = weak. md = moderate. st = strong. Size: f = fine. m = medium. Type: ma = massive. gr = granular. bl =subangular blocky. sg = single grain. cr = crumbs; [2]Percent of particles > 2 mm.

saturation (PBS); very high Melich-1 extractable-P, Al^{3+}, TOC and total N (Table 3). The concentrations of K^+, P, and Al^{3+} tend to increase in the deepest layer, while those of Ca^{2+}, Mg^{2+}, and pH tend to decrease.

The Neutral pH ornithogenic soils show high levels of labile P and similar vegetation cover as Acid pH ornithogenic soils. However, they have a high concentration of Ca^{2+}, Mg^{2+} and K^+, and a

TABLE 3 – Chemical properties of studied pedons

Pedon	*Horizon*	*Depth* cm	*pH*		Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	*H+Al*	*CEC*	*PBS*	*m*	*ESP*	*P*
			H_2O	*KCl*	---------------------- $cmol_c\ dm^{-3}$ ----------------------							---------- % ----------			$mg\ dm^{-3}$
					Non-ornithogenic soils										
LR3	A	0-5	7.52	4.61	18.84	16.46	0.24	1.53	0.00	1.90	37.07	95.10	0	4.12	109.50
	AB	5-17/20	7.74	4.93	26.30	20.01	0.17	1.18	0.00	1.10	47.66	97.70	0	2.47	170.80
	Bi	20-47/52	7.98	5.60	26.31	14.19	0.14	0.92	0.00	0.30	41.56	99.30	0	2.21	167.20
	BC	47-52-70	8.48	6.24	30.45	12.07	0.14	0.79	0.00	0.00	43.45	100.0	0	1.81	176.30
LR4	A	0-5	8.20	5.85	20.96	6.98	0.19	1.35	0.00	0.00	29.48	100.0	0	4.59	147.90
	AB	5-22/24	8.61	6.30	21.40	5.79	0.17	1.05	0.00	0.00	28.41	100.0	0	3.69	123.00
	Bi	24-45/47	8.67	6.77	22.25	5.27	0.09	0.74	0.00	0.00	28.35	100.0	0	2.62	124.50
	BC	45/47-75	8.62	6.78	24.54	5.72	0.17	0.70	0.00	0.00	31.13	100.0	0	2.25	112.80
LR5	C1	0-23	8.63	6.82	39.25	4.46	0.09	1.48	0.00	0.00	45.28	100.0	0	3.28	61.40
	C2	23-60	8.78	6.79	37.66	3.85	0.12	2.09	0.00	0.00	43.72	100.0	0	4.79	94.80
	C3	60-90	8.77	6.83	39.97	3.64	0.12	2.40	0.00	0.20	46.13	99.60	0	5.20	73.40
LR12	A	0-8/25	7.33	5.06	15.60	24.91	0.54	1.87	0.00	1.30	42.92	97.10	0	4.36	138.90
	C	8-25/30	7.41	5.06	20.86	25.01	0.54	1.83	0.00	1.60	48.24	96.80	0	3.79	117.70
LR13	A	0-8	7.62	4.79	22.01	24.98	0.32	1.92	0.00	1.10	49.23	97.80	0	3.89	124.50
	AC	8-15	6.09	4.15	20.58	22.06	0.24	1.48	0.87	3.20	44.36	93.30	1.9	3.27	101.10
	C	15-65	3.62	3.00	4.03	9.18	0.05	0.43	19.5	28.10	13.69	32.80	58.7	1.31	6.90
LR19	A	0-4	6.58	4.83	12.64	23.48	0.40	1.44	0.00	3.80	37.96	90.90	0	3.78	52.50
	AC	4-12/15	6.28	3.97	12.73	23.55	0.46	1.70	0.87	5.60	38.44	87.30	2.2	4.32	80.50
	C1	15-30/35	6.54	4.02	9.16	22.25	1.47	1.74	0.00	4.80	34.62	87.80	3.0	4.88	88.40
	C2	30/35-70	6.91	4.32	7.30	30.89	1.98	2.22	0.00	3.70	42.39	92.00	0.4	5.21	85.10
LR21	O	0-3/4	6.55	5.19	9.47	18.96	0.23	0.65	0.00	1.60	29.31	94.80	0	2.22	47.40
	A	3/4-8/10	6.92	4.54	14.72	22.34	0.20	1.26	0.00	1.70	38.52	95.80	0	3.27	62.40
	AB	10-18/20	7.58	4.97	17.69	18.28	0.13	1.04	0.00	0.60	37.14	98.40	0	2.81	88.30
	Bi	20-45/50	8.02	5.77	18.14	14.61	0.05	1.04	0.00	0.60	33.84	98.30	0	3.08	192.60
	BC	45/50-65	8.20	6.14	20.60	13.43	0.03	0.87	0.00	0.60	34.93	98.30	0	2.49	220.80
LR24	A	0-8	6.64	4.61	12.13	22.99	0.23	1.17	0.00	3.80	36.52	90.60	0	3.22	67.50
	AB	8-20	6.78	4.57	12.16	22.78	0.23	1.13	0.00	3.80	36.30	90.50	0	3.12	77.80
	BA	20-33	7.12	4.80	14.88	23.72	0.23	1.35	0.00	2.70	40.18	93.70	0	3.36	92.50
	Bi	33-52	7.37	4.72	16.37	21.90	0.18	0.83	0.00	1.10	39.28	97.30	0	2.10	186.60
					Acid pH ornithogenic soils										
LR8	O	0-5	4.88	3.77	1.85	2.45	0.09	0.45	0.48	4.50	4.84	51.80	9	8.43	79.60
	A	5-12	4.37	3.13	3.82	6.42	0.70	1.53	8.00	22.30	12.47	35.90	39.1	7.46	390.40
	AB	12-18	4.04	3.00	0.91	1.29	0.42	1.22	8.00	29.60	3.84	11.50	67.6	10.33	603.40
	BA	18-32	3.88	3.00	0.29	0.35	0.93	0.92	6.46	8.40	2.49	22.90	72.2	10.26	1199.30
	B1	32-70	3.94	3.00	0.95	0.58	1.26	0.79	6.84	41.80	3.58	7.90	65.6	7.56	1065.80
	B2	70-100	3.98	3.00	0.85	0.65	1.81	0.71	6.65	44.50	4.02	8.30	62.3	6.69	1093.80
	B3	100-120	3.85	3.00	0.41	0.38	1.08	0.71	6.17	50.60	2.58	4.90	70.5	8.16	1468.50
LR9	A	0-8	4.26	3.66	8.17	2.27	0.57	1.57	0.67	15.10	12.58	45.40	5.1	11.85	5485.10
	Cr	8-40	3.96	3.00	2.18	0.49	1.61	0.52	3.18	17.80	4.80	21.20	39.8	6.55	1004.20
					Neutral pH Ornithogenic soils										
LR15	O1	0-3/4	5.28	4.20	18.60	22.11	1.41	2.05	0.10	8.90	44.17	83.20	0.2	4.62	1037.80
	O2	¾-9/11	5.66	4.18	18.30	23.48	1.00	1.65	0.29	8.70	44.43	83.60	0.6	3.70	771.10
	OA	11-16/17	5.99	4.26	23.56	23.02	0.85	1.92	0.00	7.50	49.35	86.80	0	3.88	1290.10
	Bi1	17-37/38	7.40	5.47	29.25	24.63	0.62	1.35	0.00	1.40	55.85	97.60	0	2.41	803.00
	Bi2	37/38-60	7.61	5.72	30.65	19.33	0.67	1.44	0.00	1.40	52.09	97.40	0	2.76	837.40
	BC	60-80+	8.15	6.06	35.35	21.20	0.62	1.22	0.00	1.40	58.39	97.70	0	2.09	611.60
LR22	A	0-16	7.26	6.83	8.40	11.49	0.57	2.92	0.00	1.30	23.38	94.70	0	12.48	920.50
LR23	A	0-8/10	5.89	5.09	17.20	22.29	1.85	0.96	0.00	5.70	42.30	88.10	0	2.26	3118.30
	Bi	10-22/24	5.81	4.01	28.77	15.95	0.82	1.44	0.19	3.70	46.98	92.70	0.4	3.04	403.80
	C	24-28/30	8.40	6.64	50.49	14.80	0.00	1.57	0.00	1.30	66.86	98.10	0	2.34	122.30
	2A	30-34/36	8.53	6.63	40.99	10.92	0.00	1.48	0.00	0.60	53.39	98.90	0	2.77	120.20
	2C	34/36-90	8.35	6.88	51.72	9.34	0.08	1.52	0.00	0.60	62.66	99.10	0	2.43	155.30

CEC = cation exchange capacity; PBS = percentage of base saturation (PBS); ESP = Exchangeable Sodium Percentage pH close to neutral. They are present in areas with recent exposure to ornithogenic influence, especially at Quaternary moraines and uplifted terraces (LR15 and LR23). The principal difference between Acid and Neutral ornithogenic soils is a period of colonization by penguins and greater excrement deposition.

Mean pH for Acid ornithogenic soils studied was 4.3 (±0.33), much lower than the mean values for Neutral ornithogenic soils (7.0 ±1.2) and Non-ornithogenic soils (7.4 ±1.1) (Table 3). Such acidity is produced during guano mineralization by the production of strong acids, such as HNO_3 (Tatur & Barczuk, 1985).

In Neutral ornithogenic soils, both cation exchange capacity (CEC) and percentage of base saturation (PBS) are high and represent a eutrophic soil, contrasting with dystrophic Acid ornithogenic soils with low CEC (Table 3).

Soils formed under direct penguin influence presented a mean content of 1075.3 (±1206.4) mg dm^{-3} of P. The extremely high Melich-1 extractable-P for the highest and most ancient ornithogenic soil (LR7) indicates that P minerals constitute stable P reserves, as confirmed by XRD analysis of some pedons, besides the greater amount of P as amorphous mineral and organic form. Available-P mean in Acid ornithogenic soil is much higher than the results observed for Non-ornithogenic soils, while Ca^{2+} is lower (Table 3). Similar results were observed by Moura et al. (2012) for soils from Byers Peninsula, Livingston Island. As shown for similar soils from Maritime Antarctica (Simas et al., 2006; 2007), soil development under the same conditions is marked by instability of P-Ca phases .

Soil acidity promotes the formation of clay minerals with P-Al-K phases of varying crystallinity (Simas et al., 2006). In these pedoenvironments, phosphatization is the main soil-forming process and determines the soil's overall chemistry and ecosystem functioning (Pereira et al., 2013; Simas et al., 2007; Tatur & Barczuk, 1985).

The highest content of Melich-1 extractable-P was obtained for the first layers of the most recently abandoned rookery (LR9, Table 3). In general, high P values in depth indicate P illuviation after rookery abandonment by penguins.

Rookeries and adjacent areas are more developed than soils with no faunal influence, as observed when comparing LR8 with LR3. A stony/pebbly pavement is present at all sites but is often hidden by the well-developed and continuous vegetation in ornithogenic sites. Clear horizon differentiation occurred, and a relatively deep organic matter-rich A horizon and a phosphatic B horizon were easily identified. Surface horizons are dark and yellowish-brown due to the humus incorporation, corroborating the findings of Michel et al. (2006) and Simas et al. (2008) for soils on King George Island.

In the most developed ornithogenic soils (LR8), the surface horizons have lower P contents than the depth horizons, due to plant uptake and organic material accumulation over old layers of guano deposition, concomitant with P leaching (Table 3).

In the absence of ornithogenic activity, chemical weathering is less pronounced, and soils exhibit chemical and mineralogical characteristics mainly influenced by the parent material. Non-ornithogenic soils showed high pH, Ca^{2+}, and Mg^{2+}, as verified in LR4, LR5, and LR12. K-exchangeable results are lower than in ornithogenic soils, which receive K^{+} deposition from guano.

The mean P content in non-ornithogenic soils was 102.7±48.0 mg dm^{-3}, a value considered high for soils without penguin influence and formed from weathered basalt-andesitic rocks (Daher et al., 2019).

Even in areas with some stagnant water (LR19, LR21, and LR25), no redoximorphic features were observed, as described by Blume et al. (2002) and Simas et al. (2008) for some hydromorphic soils of the Maritime Antarctic. No features of salinization were observed in any of the pedons studied, nor podzolization, even in soils with high sand content.

Acid sulfate soils, a product of oxidation of sulfides, as described by Simas et al. (2006) and Simas et al. (2008) in Admiralty Bay, occur at a single site at Lions Rump, where they formed from sulfide-bearing andesites and related tills. It is pedon LR13, which presents a lower pH (3.62), high Al^{3+} (19.5 $cmol_c$ dm^{-3}), H+Al (28.1 $cmol_c$ dm^{-3}), and very low P (6.9 mg dm^{-3}). In the clay fraction, jarosite and smectite are the principal minerals (Figure 3). This pedon also presents traces of ashes from the last volcanic eruption from Penguin Island (nearby).

Soils from Lions Rump have relatively low clay (9.2%) and silt contents (24.9%) (Table 2), compared to other soils studied at Admiralty Bay. Clay contents are higher in Ornithogenic soils, contrasting with the results of Simas et al. (2008), who found lower clay proportions in Ornithogenic soils compared with non-ornithogenic soils. All soils are gravelly and have similar content of particles > 2 mm. The tendency to be more skeletal is verified

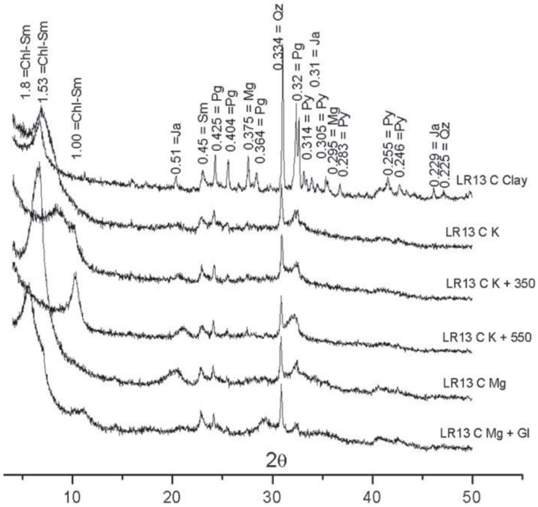

FIGURE 3 – XRD patterns of the clay fraction for the Non-ornithogenic soils from Lions Rump, Maritime Antarctica. Chl-Sm = Chlorite-Smectite Intergrade; Pg = Plagioclase Group; Ja = Jarosite; Al = Allophane; Py = Pyroxene; Mg = Maghemite.

for soils formed from Paleogene bedrock materials at higher altitudes (Table 2).

The soil structure is dominated by weak, medium-sized, blocky aggregates and moderate, medium granular features, with clear to gradual wavy horizon transitions, which may indicate weak cryoturbation (Turbels) in this area (Table 2).

Previous studies of pedons in Admiralty Bay (Michel et al., 2006; Simas et al., 2008) reported permafrost above 200 cm depth and typical cryoturbation features such as patterned ground, irregular and broken horizons, vertical orientation of stones within the soil profile, buried organic matter, and formation of silt caps were commonly observed, as indicated for Bockheim and Tarnocai (1998) and Tarnocai et al. (2004). In this study, none of the ornithogenic soils was classified as Gelisols, and cryoturbation features are not commonly observed. Soils with permafrost were recorded only above 80 m a.s.l. and at depths greater than 100 cm.

3.4 Total organic carbon and humic substances

Although biomass production by Antarctic vegetation is scarce, it frequently exceeds the decomposition capacity of local microbiota, which is limited by climate conditions (Ugolini, 1972). Then, low temperatures and moisture are crucial for the low microbial activity and humification rate of Antarctic soils (Pereira et al., 2013). Therefore, organic matter accumulates at some specific sites and plays important pedological and ecological roles (Beyer, 2000; Beyer et al., 1995; Bölter & Kandeler, 2004; Simas et al., 2008).

The sea-to-land transfer of nutrients favors vegetation development and ornithogenic soil formation at the landscape. These soils are the main terrestrial organic carbon pool of Maritime Antarctica (Simas et al., 2007). At Lions Rump, total organic carbon in ornithogenic soils is much higher than for non-ornithogenic soils (Table 4).

The fractionation of humic substances in ornithogenic soil showed 0.55 g kg^{-1}, 0.83 g kg^{-1}, and 3.67 g kg^{-1} for fulvic acids (FA), humic acids

TABLE 4 – Total organic carbon and humic substances of the studied pedons.

Pedon		*Depth (cm)*	*TOC*	*FA*	*HA*	*HU*	*HA/FA*
		---------------- *dag kg* $^{-1}$ ---------------					
Non-ornithogenic soils							
LR3	A	0-5	0.23	0.01	0.00	0.21	–
	AB	5-17/20	0.17	0.10	0.00	0.07	–
	Bi	20-47/52	0.14	0.00	0.00	0.13	–
LR4	A	0.43	0.14	0.00	0.07	0.05	0.0
	AB	0.46	0.14	0.00	0.00	0.13	0.0
	Bi	24-45/47	0.17	0.00	0.00	0.15	0.0
LR5	C1	0-23	0.27	0.05	0.00	0.23	0.0
LR13	A	0-8	0.17	0.00	0.00	0.15	0.0
	C	15-65	0.12	0.01	0.00	0.11	0.0
LR19	A	0-4	1.92	0.31	0.21	1.25	0.7
	C1	15-30/35	0.33	0.04	0.01	0.23	0.3
LR24	A	0-8	1.20	0.21	0.09	0.83	0.4
	Bi	33-52	0.20	0.01	0.00	0.17	0.0
Acid pH ornithogenic soils							
LR8	O	0-5	18.70	1.69	3.11	12.90	1.8
	A	5-12	3.32	0.48	0.48	2.36	1.0
	BA	18-32	1.26	0.22	0.23	0.81	1.0
	B3	100-120	1.26	0.25	0.30	0.72	1.2
LR9	A	0-8	4.24	0.48	0.51	2.96	1.1
	Cr	8-40	1.48	0.19	0.34	0.95	1.8
Neutral pH ornithogenic soils							
LR15	O1	0-3/4	4.17	0.39	0.92	2.61	2.4
	OA	11-16/17	1.96	0.24	0.34	1.17	1.4
	Bi1	17-37/38	0.36	0.17	0.00	0.15	0.0
	Bi2	37/38-60	0.26	0.01	0.00	0.25	0.0
LR22	A	0-16	2.82	0.50	0.22	2.01	0.4
LR23	Bi	10-22/24	0.24	0.04	0.00	0.20	0.0
	2A	30-34/36	0.16	0.02	0.00	0.14	0.0
	2C	34/36-90	0.33	0.00	0.05	0.22	0.0

(HA), and humin (HU), respectively (Table 4). In ornithogenic soils, HU contents are high due to the dense cover of higher plants (*D. antarctica* and *C. quitensis*), which are responsible for the incorporation of lignin from the root system into the soil. However, this HU is likely not an actual humic substance, as it is a residual organic material that has not decomposed.

HA and FA fractions are probably present because they are provided by guano. In Non-ornithogenic soils, we found averages of 0.1 g kg^{-1} for FA, 0.3 g kg^{-1} for humin (HU), and no detectable humic acids (Table 4). These low contents are justified by the almost absence of vegetation on these soils. Pereira et al. (2013) found in soils at Hope Bay, Antarctic Peninsula, HA dominating other carbon forms, where vegetation is principally formed by mosses and lichen, where a high HA/FA ratio is indicative of a higher degree of humification.

Sites dominated by *D. antarctica* and/or *C. quitensis* (LR8 and LR15) showed higher TOC contents in depth due to the presence of lignin-bearing tissues and proper root systems (Simas et al., 2007). On the other hand, soils covered with *P. crispa* (LR23) or mosses (LR21) present an abrupt decrease in TOC with depth. Although ornithogenic soils exhibit a high TOC content, no umbric epipedon was observed. For Non-ornithogenic soils, HU is almost the only form of organic compounds. It is practically absent from organic matter labile forms.

The tendency to increase the HA/FA ratio in the depth of Acid ornithogenic soils, as also observed by Michel et al. (2006), is associated with the migration and reaction of organic matter along the pedon, resulting in polycondensation and the accumulation of more recalcitrant humic substances in depth.

3.5 Total elemental composition

Total mean contents of CaO, MgO, and K_2O were respectively 0.24 g kg^{-1}, 0.05 g kg^{-1}, and 1.02 g kg^{-1} for Acid ornithogenic soils, 0.51 g kg^{-1}, 0.08 g kg^{-1}, and 0.43 g kg^{-1} for Neutral ornithogenic soils, and 0.48 g kg^{-1}, 0.11 g kg^{-1}, and 0.72 g kg^{-1} for Non-ornithogenic soils (Table 5). These data show a reduction in CaO and MgO contents and an increase in K_2O in Acid ornithogenic soil, which is derived

TABLE 5 – Total elemental composition in < 2 mm air-dried soil samples from selected pedons

Pedon	*Horizon*	*Depth cm*	*CaO*	*MgO*	*K_2O*	*F_2O_3*	*Al_2O_3*	*MnO*	*P_2O_5*	*Cu*	*Zn*	*Cd*	*As*	*Cr*	*Pb*
			dag kg^{-1}							*mg kg^{-1}*					
Non-ornithogenic soil															
LR3	A	0-5	0.64	0.15	0.89	8.58	3.15	0.12	0.16	92.2	87.2	11.1	13.2	103.4	22.5
	AB	5-17/20	0.74	0.14	0.88	6.88	3.31	0.11	0.15	24.9	95.8	11.5	27.9	94.0	39.7
LR4	A	0-5	0.43	0.10	1.17	6.99	3.31	0.09	0.12	55.5	74.9	9.5	20.9	82.8	22.6
	Bi	24-45/47	0.46	0.12	1.18	7.17	3.13	0.10	0.13	60.5	85.9	8.6	14.8	73.5	19.1
LR5	C1	0-23	1.31	0.26	0.62	8.12	2.57	0.10	0.12	89.9	74.6	10.2	16.3	301.7	24.0
LR13	A	0-8	0.36	0.07	0.12	9.63	7.04	0.05	0.17	30.6	63.4	6.3	24.8	27.8	21.1
	C	15-65	0.13	0.04	0.86	11.47	5.50	0.02	0.23	46.4	34.3	11.0	27.9	17.9	27.7
LR19	A	0-4	0.37	0.11	0.51	6.92	3.50	0.06	0.21	38.6	60.9	5.9	7.9	77.3	11.3
	C1	15-30/35	0.35	0.10	0.55	8.50	3.93	0.04	0.29	46.1	66.8	4.0	6.5	37.5	4.0
LR24	A	0-8	0.26	0.08	0.57	8.42	3.88	0.06	0.22	34.3	56.4	5.0	4.0	50.9	6.7
	Bi	33-52	0.26	0.07	0.59	8.11	4.25	0.06	0.15	33.1	60.9	6.1	7.3	31.7	10.9
Acid pH Ornithogenic soils															
LR8	O	0-5	0.36	0.13	1.01	5.35	4.95	0.05	0.61	75.3	75.4	11.3	34.0	62.0	44.0
	A	5-12	0.31	0.08	1.00	7.36	5.09	0.05	1.81	69.0	69.7	7.8	23.4	35.4	17.4
	BA	18-32	0.15	0.02	1.00	9.28	5.00	0.03	6.50	72.6	72.2	7.5	19.9	30.1	15.0
	B3	100-120	0.13	0.02	1.00	10.13	5.40	0.03	7.47	75.0	69.9	8.8	23.8	33.4	19.4
LR9	A	0-8	0.34	0.04	1.11	6.34	3.87	0.03	5.01	165.8	159.1	6.4	13.0	39.9	13.9
	Cr	8-40	0.16	0.02	1.02	7.98	5.06	0.02	12.32	157.1	105.8	8.7	37.8	35.9	28.2
Neutral pH Ornithogenic soils															
LR15	O1	0-3/4	0.66	0.21	0.73	7.84	3.53	0.07	0.82	61.6	96.2	7.9	20.2	142.6	21.6
	OA	11-16/17	0.96	0.29	0.72	8.00	3.25	0.09	0.72	53.3	93.9	7.8	21.5	157.7	18.6
	Bi1	17-37/38	0.95	0.17	0.69	8.19	2.93	0.10	0.38	51.6	82.2	8.2	18.6	170.1	24.7
LR22	A	0-16	0.50	0.10	0.79	7.86	3.79	0.05	1.00	62.3	89.1	4.8	4.1	74.3	5.9
LR23	Bi	10-22/24	0.36	0.10	0.51	9.47	3.35	0.06	0.25	47.0	66.0	5.5	7.3	45.8	3.8
	2A	30-34/36	0.41	0.06	0.52	9.25	3.14	0.06	0.16	41.5	65.9	6.2	5.5	64.8	8.2
	2C	34/36-90	0.22	0.03	1.91	10.31	3.84	0.07	0.17	80.4	87.4	10.5	12.8	48.0	14.7

from Ca and Mg leaching, K addition from guano and the formation of K-rich phosphate minerals such as taranakite.

Plagioclases were detected in all soils. In this case, the presence of these primary minerals in the clay fraction indicates a limited chemical weathering and the effect of cryoclasty, decreasing particle size and increasing CEC. The higher content of total K_2O in comparison to K^+ suggests that K is primarily present in non-exchangeable forms, possibly associated with the formation of phosphate clays, typical minerals from the phosphatization process (Pereira et al., 2013), as well as plagioclase occurrence (Figure 4). In this case, the high levels of K and P, associated with ornithogenesis, create unique conditions and typical minerals found only in ornithogenic soils, compared with other local soils.

Mean contents of total P_2O_5 were 5.62 g kg^{-1} for Acid ornithogenic soils, 0.43 g kg^{-1} for Neutral ornithogenic soils, and 0.18 g kg^{-1} for Non-ornithogenic soils (Table 5). The P enrichment in sites with previous or current ornithogenesis influence is significant. The P total in Acid ornithogenic soils is significantly higher than in Non-ornithogenic ones, which confirms the importance of avifaunal influence in soil formation in Antarctica.

Mean total contents of Fe_2O_3 and Al_2O_3, were respectively, 7.74 g kg^{-1} and 4.90 g kg^{-1} for Acid ornithogenic soils, 8.61 g kg^{-1} and 3.55 g kg^{-1} for Neutral ornithogenic soils, and 8.25 g kg^{-1} and 3.96 g kg^{-1} for Non-Ornithogenic soils (Table 5). The results indicate that oxides are closely related to the parent material, and no influence of guano on these contents was observed. However, a slightly higher content of Al_2O_3 in Acid ornithogenic soils, compared to others, may be related to more intensive weathering followed by leaching of bases and accumulation of Al, in detriment of Fe, due to the higher stability of Al in acid conditions, and formation of aluminosilicates.

Mean total heavy metal contents (Table 5) were 17.23 mg kg^{-1} (As), 7.94 mg kg^{-1} (Cd), 76.60 mg kg^{-1} (Cr), 65.19 mg kg^{-1} (Cu), 18.54 mg kg^{-1} (Pb), and 78.91 mg kg^{-1} (Zn). These contents are lower than observed for Schaefer et al. (2015), except for Cd. No significant difference was observed among soil groups in heavy metal concentrations (Table 5), indicating the influence of parent material lithology on these contents. Examples of that are higher levels of Zn determined in LR3, LR9, and LR15 for the Nonornithogenic, Acid, and Neutral pH ornithogenic groups, respectively.

Regarding the distribution of metals within the profiles, some trace elements, such as Cr, Pb, and Zn, exhibited values and patterns higher and more distinct than those reported by Castro et al. (2022) for ornithogenic soils, indicating that no regular or well-defined distribution pattern exists among our soil groups. Acid pH ornithogenic soils (e.g., LR8) showed twice the Pb concentration (44.0 mg kg^{-1}) in the surface layer (0-5 cm) compared with the other soils (average of 21 mg kg^{-1}) (Table 5). This finding supports Castro et al. (2021), who suggested that the origin of Pb in ornithogenic soils may be linked to increasing anthropogenic

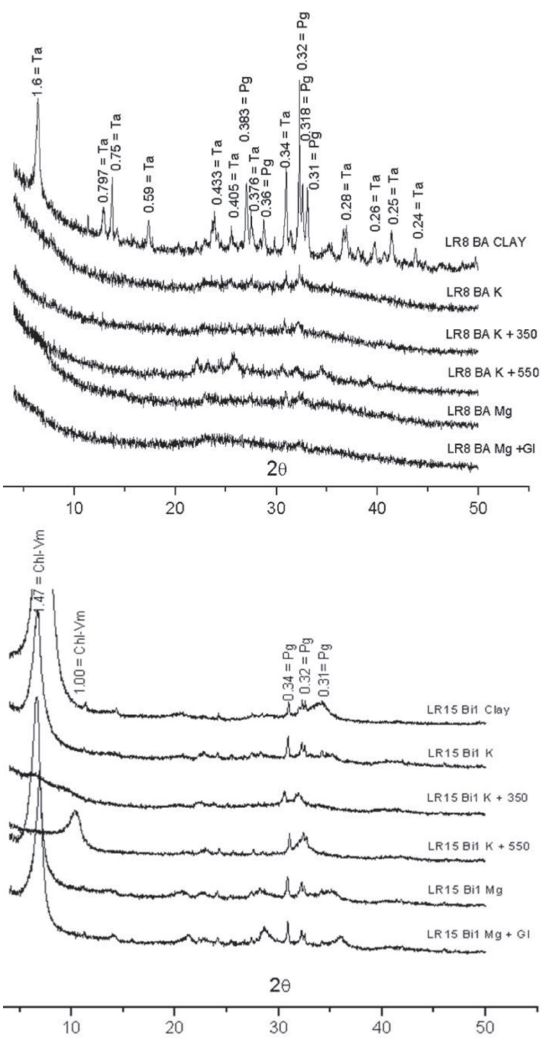

FIGURE 4 – XRD patterns of clay fraction for Acid ornithogenic (LR8) and Neutral ornithogenic soils (LR15) from Lions Rump, Maritime Antarctica. Ta = Taranakite; Pg = Plagioclase Group; Clh-Vm = Chlorite-Vermiculite Intergrade.

contamination of the Southern Ocean, indicating a potential indirect effect of human-derived pollution on the Antarctic terrestrial environment. However, studies reporting heavy-metal contamination from anthropogenic activities on land, particularly in areas near research stations, have been conducted by Santos et al. (2005; 2007), Chaparro et al. (2007; 2011), Guerra et al. (2011), and Lu et al. (2012).

3.6 Soil mineralogy

The X-ray diffraction patterns for Non-ornithogenic soils showed the presence of a chlorite-vermiculite intergrade, represented by peaks at 1.5 nm in the clay fraction, which was not altered by treatments with KCl, Mg, and Mg + glycol saturation. However, this peak collapsed to 1.00 nm after heating at 350 °C and 550 °C (Figures 2 and 4).

Minerals like the feldspar group, including plagioclases, anorthite, albite, and others, are identified from XRD peaks at 0.375, 0.330, 0.321, 0.318, and 0.303 nm. The presence of feldspar in the clay fraction is related to the incipient leaching of bases and Si, contributing to low chemical weathering in the thermodynamic equilibrium involving Ca, Mg, and K. These results suggest that, although the Maritime Antarctic is warmer and wetter than Continental Antarctica, the chemical weathering process is still limited in this region as well. The absence of kaolinite is also another evidence of incipient weathering in these Non-ornithogenic soils, even though this mineral has been found in a few Antarctic soils, mainly in acid sulfate soils (Siqueira et al. 2022).

No difference in the mineralogical composition of Non-ornithogenic soils was verified between Gelisols (LR3) and Inceptisols (LR12) (Figure 5) from the same parental material, confirming that, besides the absence of permafrost in the Non-ornithogenic Inceptisols, limited soil formation occurs mainly through physical processes such as pedoturbation and cryoclasty.

XRD patterns for clay fraction of LR15, a “neutral pH ornithogenic soil” (Figure 4), indicate no mineralogy alteration after short avifauna influence, therefore, despite the high amount of P and TOC input by birds, short soil exposure to the penguin rookery was not enough to promote phosphatization process, which is a transformation of silicate clay minerals into phosphates (Almeida et al., 2021). A detailed study of clay-sized minerals in Antarctic soils with varying degrees of ornithogenic influence is presented by Almeida et al. (2021), Pereira et al. (2013), Schaefer et al. (2008), and Simas et al. (2006).

Phosphatization is evident in LR8 (Figure 4), where most silicate clay minerals were transformed into crystalline and non-crystalline phosphates, mainly taranakite. The primary evidence for this is the complete absence of 2:1 secondary silicate clay minerals, as also observed in the majority of ornithogenic soils. Taranakite is poorly crystallized, as peaks disappear after any clay treatment. The clay treatment for XRD analysis is important for ornithogenic soils to eliminate inconclusions between 2:1 and phosphate minerals at the 1.6 nm peak.

The weathering, transforming primary silicate minerals into 2:1 and 1:1 clay minerals, is

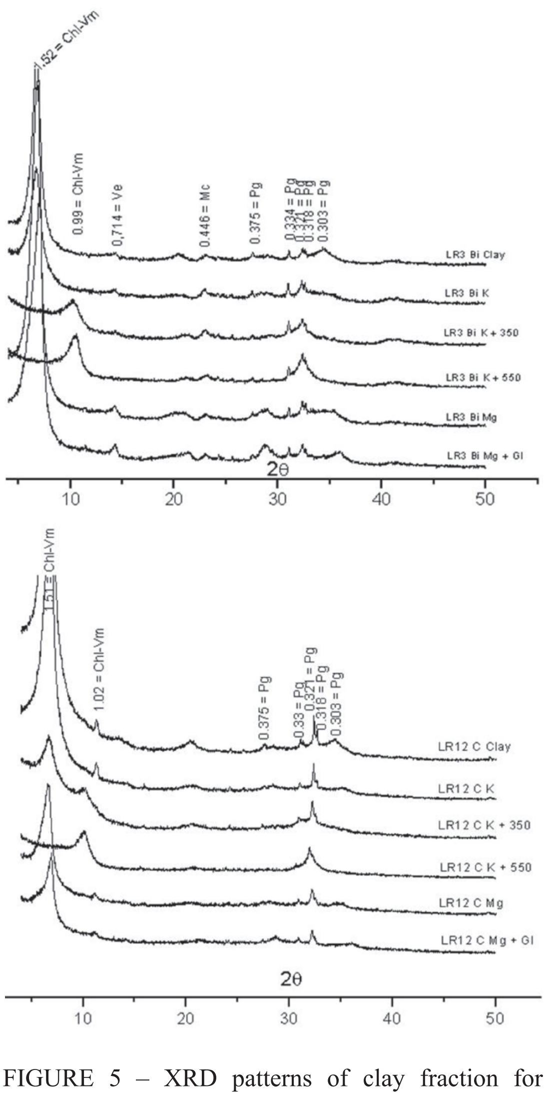

FIGURE 5 – XRD patterns of clay fraction for Non-ornithogenic soils from Lions Rump, Maritime Antarctica. Ve = Vermiculite; Pg = Plagioclase Group; Chl-Vm = Chlorite-Vermiculite Integrade.

uncommon in Antarctic ornithogenic soils. When primary minerals are weathered, the bases in solution can be complexed by P, reducing bases' activity to levels not enough to form secondary minerals.

LR13 represents an acid soil formed from sulfide-bearing andesites and related tills present in the top part of Lions Rump. This site is well-drained and shows clear cryoturbation features, including dead ice and peculiar yellowish colors. The oxidation of sulfides promotes soil acidification, leading to secondary sulfate minerals such as jarosite (Figure 3) and sulfuric horizons similar to those described by Simas et al. (2006) in Admiralty Bay. Contrary to Simas et al. (2008), who found kaolinite in the Antarctic clay fraction, at Lions Rump, this mineral was not detected in acid sulfide soils.

The presence of clay-sized pyroxene and plagioclase, and the absence of kaolinite, suggest an incipient degree of chemical weathering, despite the advanced acidification process. The main secondary silicate clay mineral present in this soil is chlorite-smectite intergrade, as indicated by a peak at 1.5 nm, which remains after K saturation, shifts to 1.8 nm after Mg+glycol treatment, and collapses to 1.0 nm after heating to 550 °C. Maghemite and jarosite are also detected, corroborated by the expressive chrome color (10YR 5.5/8). Allophane is probably present and is derived from ashes deposited on the sulfuric materials and mixed by the cryoturbation process. These ashes came from the last eruption on Penguin Island, and their evidence can be observed covering soils in marine terraces.

According to the WRB system, acid sulfate soils are classified as Turbi-thionic Cryosols (Tarnocai et al., 2004). However, as previously observed by Simas et al. (2008), in the Soil Taxonomy system, the sulfuric qualifier applies only to Aquiturbels, which is clearly not the case for these well-drained and oxidized soils. Therefore, our studies reinforce the proposal by Simas et al. (2008) to include the Sulfuric Haploturbel to classify well-drained cryoturbated soils with sulfuric materials in the upper 100 cm depth.

All soils studied presented a high Feo/Fed ratio (Table 6), which usually indicates high amounts of poorly crystalline forms and/or soil-less developed, according to the soil classification presented. However, in Lions Rump, the highest Feo/Fed ratio is found in LR8 and LR9, both which are Acid ornithogenic and more developed soils in the study area. The predominance of low-crystallinity Fe minerals in Antarctic ornithogenic soils, in which part of Al and Fe may be present as organometallic complexes due to the high TOC, can explain these results, as indicated by Simas et al. (2007).

According to Tatur and Barczuk (1985), the "phosphatization" process comprises chemical weathering of rock minerals and the formation of amorphous Al and Fe minerals. These phases react with ornithogenic P, K, and N to form amorphous and crystalline secondary phosphates. According to Simas et al. (2006), non-crystalline phases are important soil components and reach >75% of the clay fraction in some ornithogenic soils.

Simas et al. (2006) found crystalline phosphates occurring only in soils directly affected by penguins (abandoned and active rookeries), specifically in LR8 and LR9 pedons from Lions Rump. The incongruent dissolution of crystalline Al-Fe phosphates, with the formation of amorphous P-rich phases, is considered the most common transformation with increasing age of the abandonment site (Tatur et al., 1997) and maintains high levels of labile P forms. On the other hand, in pedons with lower penguin influence (LR15 and LR23), P inputs are lower too, and probably no crystalline phosphates are present. Therefore, the chemical characteristics of these pedons are controlled by highly reactive non-crystalline P minerals.

3.7 Soil mapping

The soil survey is a preliminary soil map of Lions Rump (Figure 6). Soil units mapped were: Lithic Cryorthents (2.55 ha), Typic Dystrogelepts ornithic (0.93 ha), Typic Gelifluvents ornithic (1.75 ha), Typic Gelorthents ornithic (1.69 ha), Typic Haplogelepts ornithic (9.45 ha); Association: Turbic Haplogelepts and Typic Gelorthents (30.91 ha), Association: Oxyaquic Cryopsamments and Vitrandic Cryopsamments (15.45 ha), Association: Typic Haplogelepts and Typic Gelorthents (3.44 ha), Association: Typic Haploturbels and Lithic Haploturbels (163.86 ha).

Typic Dystrogelepts ornithic and Typic Gelorthents ornithic are the main vegetated soils in Lions Rump, which possibly represents one of the first ice-free areas colonized by penguins in Maritime Antarctica. Typic Dystrogelepts ornithic may represent the deepest, most structured and reddish soils described in Maritime Antarctica. Typic Haplogelepts ornithic represent the main

TABLE 6 – Fe, Al, and P contents extracted by citrate-bicarbonate-dithionite and ammonium oxalate from selected horizons of some studied pedons.

Pedon	Horizon	Prof. (cm)	------- CBD (Σ[1]) -------			-------- Oxalate --------			Fe_o / Fe_d	Al_o / Al_d	P_o / P_d
			Fe_2O_3	Al_2O_3	P_2O_5	Fe_2O_3	Al_2O_3	P_2O_5			
			------------------- dag kg^{-1} -------------------								
Non-ornithogenic soils											
LR3	A	0-5	1.70	0.47	0.11	0.46	0.40	0.08	0.27	0.85	0.73
	AB	5-17/20	1.86	0.55	0.10	0.46	0.39	0.08	0.25	0.71	0.80
	Bi	17/20-47/52	1.00	0.24	0.11	0.44	0.35	0.08	0.43	1.46	0.73
LR4	A	0-5	1.31	0.19	0.11	0.19	0.18	0.04	0.14	0.95	0.36
	AB	5-22/24	1.85	0.37	0.11	0.30	0.28	0.05	0.16	0.76	0.45
	Bi	22/24-45/47	1.70	0.36	0.10	0.33	0.29	0.05	0.20	0.81	0.50
LR5	C1	0-23	1.64	0.52	0.10	0.66	0.47	0.03	0.40	0.90	0.30
LR13	A	0-8	1.92	0.24	0.13	0.37	0.32	0.05	0.19	1.33	0.38
	C	15-65	6.60	0.66	0.22	1.45	0.37	0.05	0.22	0.56	0.23
LR19	A	0-4	1.69	0.49	0.15	0.69	0.40	0.09	0.41	0.82	0.60
	C1	12/15-30/35	1.65	0.42	0.18	0.57	0.36	0.14	0.34	0.86	0.78
LR24	A	0-8	1.80	0.52	0.16	0.42	0.48	0.10	0.24	0.92	0.63
	Bi	33-52	1.58	0.24	0.12	0.25	0.23	0.06	0.16	0.96	0.50
Acid pH ornithogenic soils											
LR8	O	0-5	1.72	0.73	0.51	0.46	0.32	0.31	0.27	0.44	0.61
	A	5-12	3.05	1.09	1.56	1.65	0.69	1.53	0.54	0.63	0.98
	BA	18-32	5.01	3.84	5.89	3.36	2.10	5.82	0.67	0.55	0.99
	B3	100-120	5.79	4.99	6.44	3.93	3.22	6.89	0.68	0.65	1.07
LR9	A	0-8	2.27	0.93	2.40	1.48	0.52	2.82	0.65	0.56	1.18
	Cr	8-40	2.63	2.91	4.48	0.78	1.16	2.61	0.30	0.40	0.58
Neutral pH ornithogenic soils											
LR15	O1	0-3/4	1.70	0.75	0.60	0.57	0.52	0.56	0.34	0.69	0.93
	OA	9/11-16/17	1.63	0.73	0.53	0.49	0.54	0.51	0.30	0.74	0.96
	Bi1	16/17-37/38	1.36	0.42	0.27	0.35	0.39	0.21	0.25	0.93	0.78
	Bi2	37/38-60	1.43	0.47	0.31	0.37	0.42	0.26	0.26	0.89	0.84
LR22	A	0-16	1.67	0.45	0.71	0.58	0.24	0.52	0.34	0.53	0.73
LR23	Bi	8/10-22/24	1.63	0.33	0.16	0.29	0.26	0.11	0.18	0.79	0.69
	2A	28/30-34/36	1.67	0.17	0.12	0.23	0.20	0.05	0.14	1.18	0.42
	2C	34/36-90	2.56	0.24	0.10	0.27	0.21	0.06	0.10	0.88	0.60

[1]Sum of extractions.

soils on the first and second moraine levels from the White Eagle Glacier. Typic Haploturbels and Lithic Haploturbels are present only above 80 m a.s.l., especially on the top areas and paraglacial spots, and represent Gelisols, with gelic materials within 100 cm of the soil surface and permafrost within 200 cm from the soil surface. Despite their occurrence only at higher altitudes, they represent the largest soil cover in the studied area. Typic Haploturbels and Lithic Haploturbels are present at the edge of White Eagle Glacier, where the cryoturbation process is more expressive.

Turbic Haplogelepts and Typic Gelorthents occur between 40 and 80 m a.s.l., in areas without bird-nesting influence and with no permafrost within the upper 200 cm of the profile. Vitrandic Cryopsamments and Oxyaquic Cryopsamments dominated the first level of terraces and former beaches along the coastal area. Other soils classified are present in very limited areas: Lithic Cryorthents ornithic, in the sea stacks rock outcrops (basaltic plugs) close to the beach, Typic Gelifluvents ornithic, in a small area on a glacial alluvial fan, and Typic Haplorthels, representing

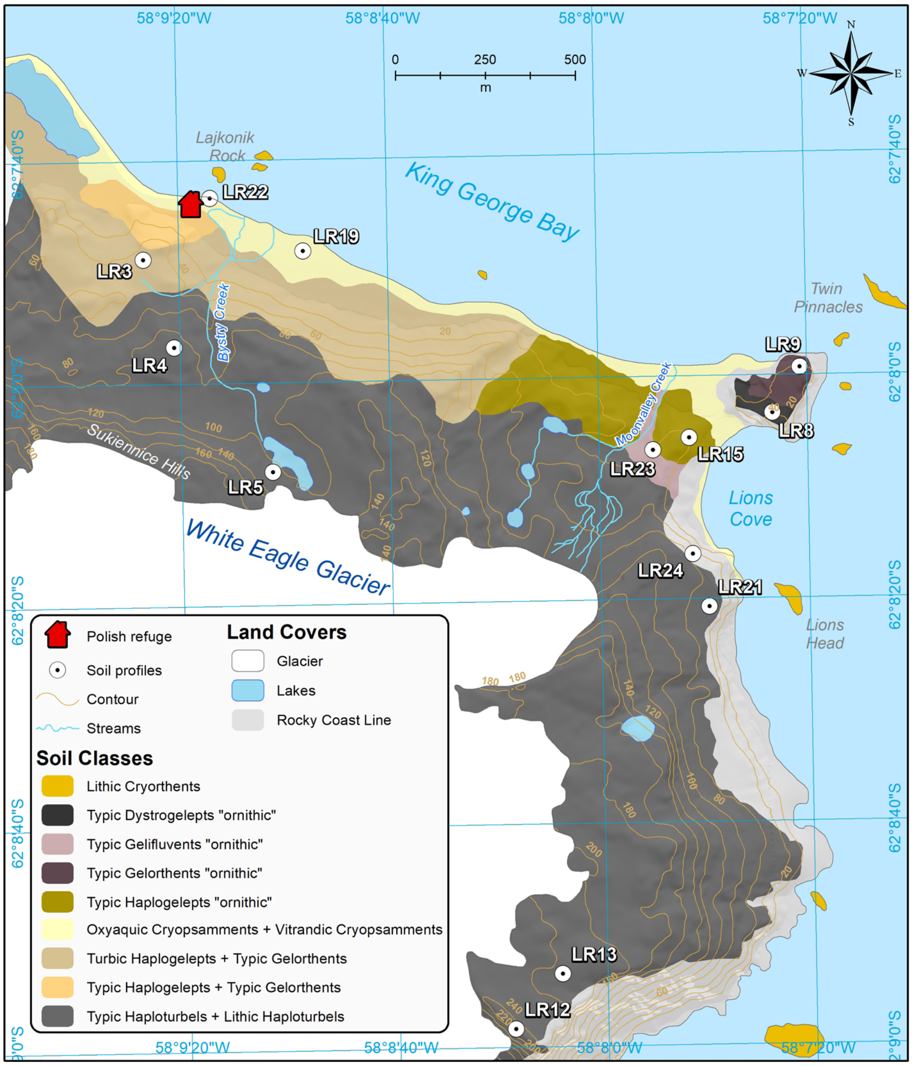

FIGURE 6 – Soil classification map showing the location of the 13 soil profiles collected at Lions Rump, King George Island, Maritime Antarctica.

an acid sulfide soil formed from sulfide-bearing andesites and related tills present in the top part of Lions Rump.

4 CONCLUSIONS

The soils of Lions Rump show a strong interaction between geology, biological inputs, and cryogenic processes.

In upland areas lacking vegetation and ornithogenic influence, soil development mainly depends on the physical weathering of basaltic till, resulting in chemically poor and weakly developed profiles. Conversely, long-term guano inputs significantly alter soil properties, causing acidification, increased mineral weathering, and the buildup of amorphous and crystalline Fe- and Al-phosphates.

Phosphatization emerges as the dominant pedogenic process in the area, generating phosphorus-rich clay fractions and sustaining elevated P reservoirs that persist long after penguin rookery abandonment. These enriched substrates promote higher plant productivity and favor the establishment of the native angiosperms *Deschampsia antarctica* and *Colobanthus quitensis*.

Soils influenced by penguin activity also function as significant terrestrial organic carbon sinks, reflecting both high organic inputs and limited decomposition under cold climatic conditions. At the landscape scale, the predominance of

Haplorthels and Haploturbels in the upper ice-free zones highlights the role of permafrost and cryoturbation in shaping soil distribution.

Together, these findings demonstrate that ornithogenic activity remains a key ecological driver in Maritime Antarctica, with lasting effects on soil chemistry, mineralogy, and ecosystem functioning.

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