



Micromorphological and microchemical indicators of pedogenesis in Ornithogenic Cryosols (Gelisols) of Hope Bay, Antarctic Peninsula

Thiago T.C. Pereira ^{a,*}, Carlos Ernesto G.R. Schaefer ^a, João C. Ker ^a, Cecília C. Almeida ^a, Ivan C.C. Almeida ^b

^a Departamento de Solos, Universidade Federal de Viçosa, Av. PH Rolfs s/n. Viçosa, 36570-000, Minas Gerais, Brazil

^b Instituto Federal do Norte de Minas Gerais, Fazenda São Geraldo, s/n km. 06, 39480-000, Januária, Minas Gerais, Brazil

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ABSTRACT

Micromorphological investigations of Antarctic soils are comparatively scarce, however, they could help understand the genesis of cryogenic soils under extreme polar conditions and different biotic factors. In most areas of Maritime Antarctica, the soil structure is apparently influenced by the local lithology, cryoturbation, guano deposition and reaction of guano solutions. The present study was carried out in Hope Bay, in the northern part of the Antarctic Peninsula, possibly one of the oldest sites of penguin occupation in the region. We describe and analyze the most important micro and sub-microscopic features of selected Ornithogenic Cryosols (Gelisols) from this part of Antarctic Peninsula, representing a transitional climatic zone between the wetter South Shetlands and the much drier Weddell Sea sector. Nine pedons representing the main ornithogenic soils found in ice-free areas of Hope Bay were selected for the micromorphological study. Undisturbed soil blocks were sampled at different depths, ranging between 0 and 30 cm. The microstructure and sub-microstructure were further investigated using a JEOL 8200 and a Zeiss scanning electron microscopes, both coupled with a microprobe (SEM/WDS). These pedons have a very limited surface accumulation of organic matter formed by mosses and lichens, changing abruptly to a mineral phosphatic horizon of bleached colours, and usually hardcemented by ice. A small to medium-sized granular structure is generally observed, with ovoidal, subrounded forms, including several well-defined ornithogenic materials, such as P-rich organic remains, nodular phosphates forms and minute fragments of bone apatite. The chemical composition of ornithogenic materials and phosphatic coatings indicates the presence of discrete forms of taranakite, minyulite, leucophosphite, struvite and fluorapatite, typical of phosphatization process in these soils. Phosphatization and enhanced chemical alteration of the substrate and is one of the main soil-forming process in ornithogenic soils, resulting in P-rich ovoidal aggregates formation. P-rich solutions penetrate desiccation fractures and cleavage planes in large clasts and react preferably with plagioclases. P reacts with Al and Fe to form various amorphous and crystalline P phases. Present day permafrost cementation of deeper phosphate layers indicate that warmer/wetter conditions occurred in the past, during which P was leached downwards and reacted with the rock substrates, developing stable ovoidal aggregates, now incorporated in ice-cemented subsurface horizon.

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1. Introduction

Micromorphological investigations of Antarctic soils are few (van Vliet-Lanöe et al., 2004). Pioneering works on the micromorphology of the Antarctic soils were made by Fitzpatrick (1956) and Kubierna (1970). Micromorphological analysis makes it possible to study the interrelationships between the various individual components, particles, and pores that make up sediments and soils. With regard to Antarctic soils, the micromorphological and microchemical studies can reveal important information regarding soil genesis and physical-chemical behavior (Schaefer et al., 2008).

At present, rock-inherited features, and secondary clays dominate cold regions and mountain soils, which also are subject to cryoturbation

processes and reduced rates of soil development (van Vliet-Lanöe et al., 2004). The microstructure development in these environments is greatly influenced by the local lithology, and, in some cases, by the reaction of large amounts of guano. Different types of platy and granular fabrics (Schaefer et al., 2008; van Vliet-Lanöe, 1985) and eluviation-illuviation processes (Fox and Protz, 1981) are commonly reported in cryogenic soils from different cold environment.

A granular microstructure comprised of a granic/granoidic fabric is commonly observed in surface horizons and is replaced by a coalesced microstructure with depth (Schaefer et al., 2008; Smith et al., 1991; Tamocai et al., 1993; White and Fox, 1997), and by an orbicular fabric (van Vliet-Lanöe et al., 2004). Platy structure having a banded fabric occurs in Cryosols subjected to freezing and thawing processes (van Vliet-Lanöe, 1985). Despite one the oldest human-visited region in Antarctica, no detailed pedological or micromorphological studies have been conducted in Cryosols from the Antarctic Peninsula. However, this area has a transitional climate between the dry, cold Polar Desert of

* Corresponding author. Tel.: +55 31 85977170.

E-mail address: torresthiago@yahoo.com.br (T.T.C. Pereira).

the Weddell Sea islands and the warmer, wettest South Shetlands archipelago.

Soils from Maritime Antarctica are generally more developed than those from drier and colder climatic zones of Antarctica (Blume et al., 2004; Michel et al., 2006). In Hope Bay, we identified and characterized five soil units, highlighting: i) Turbic Cryosol (Ornithic)–(Ornithogenic Haploturbels); and ii) Turbic Cryosol (Lithic)–(Lithic Haploturbels). The occurrence of permafrost in the first 30 cm along almost the whole extension of Hope Bay has a strong regulating effect on soil leaching and development processes.

Although periglacial, physical weathering is undoubtedly a major soil-forming process in that part of Antarctica, chemical weathering also occurs, notably in ornithogenic soils (Michel et al., 2006; Simas et al., 2006). These soils are strongly affected by sea–land transfers of nutrients by birds, mostly penguins, through deposition and reaction of large amounts of guano during the austral summer. The fine fraction of these soils contains mainly phosphates of various chemical and mineral compositions (Tatur and Keck, 1990). In these soils, a particular and complex process of deep soil phosphatization occurs, which has been described in detail by Tatur and Barczuk (1985), Tatur (1989), Schaefer et al. (2004), and Simas et al. (2007).

The present study was carried out in Hope Bay, in the northern part of the Antarctic Peninsula, possibly one of the oldest sites of penguin occupation in the region. The most important micro and sub-microscopic features were described and analysed to assess their influences on genesis of ornithogenic soils from this part of Antarctic Peninsula, representing a transitional climatic zone between the humid South Shetlands archipelago and the drier Weddell Sea sector.

2. Material and methods

2.1. Study area

The study was conducted in Hope Bay, in the Northern end of the Antarctic Peninsula (Fig. 1). The area is bordered in the South by

Mount Flora (520 m asl) and in the East by the Buenos Aires glacier, whose snout reaches over 100 m. SCAR (2002) defined the area of Mount Flora and surroundings as an Antarctic Specially Protected Area (ASPA 148). Excluding Mount Flora, the ice-free area between the sea and the glaciers covers a region of approximately 3 km², with average elevations of ≤ 100 m (Birkenmajer, 1993a, Martín-Serrano et al., 2005).

According to Köppen's classification, the region is part of the EF (polar) climate. The average temperature of Hope Bay measured at Esperanza Station, between 1952 and 2010 was -5.1 °C, with annual precipitation of approximately 150 mm, characterizing a polar semi-desert climate.

The geology of Hope Bay is composed of a metasedimentary (Trinity Peninsula Group–Hope Bay Formation–Permo–Carboniferous: marine siliciclastic turbidites and sandstones), sedimentary (Botany Bay Group–Mount Flora Formation – Lower to Middle Jurassic: sandstones, conglomerates and bituminous schists) and volcanic rock sequences (Antarctic Peninsula Volcanic Group–Kenney Glacier Formation – Lower Cretaceous: rhyolite-dacites, ignimbrites, conglomerates and cemented tuff) (Birkenmajer 1993b; del Valle et al. 2001; SCAR, 2002).

The geomorphology is related to both paraglacial and periglacial processes and landforms, reflecting the widespread late Quaternary retreat of glaciers (Martín-Serrano et al., 2005), with shorter intervals of minor glacial advances. Most geomorphic processes are related to the coastal environment, with persistent winds, summer melting, increasing periglacial erosion, and thermokarst features are common.

2.2. Soil sampling

Nine pedons representing the main ornithogenic soils found in ice-free areas of Hope Bay were selected for the micromorphological study, and all were classified as Cryosols/Gelisols, except for pedon 16 (Table 1). Detailed chemical, physical and mineralogical data regarding these soils are found in Pereira et al. (in press). The soil depths considered in the micromorphological analyses were 0–30 cm for all pedons.

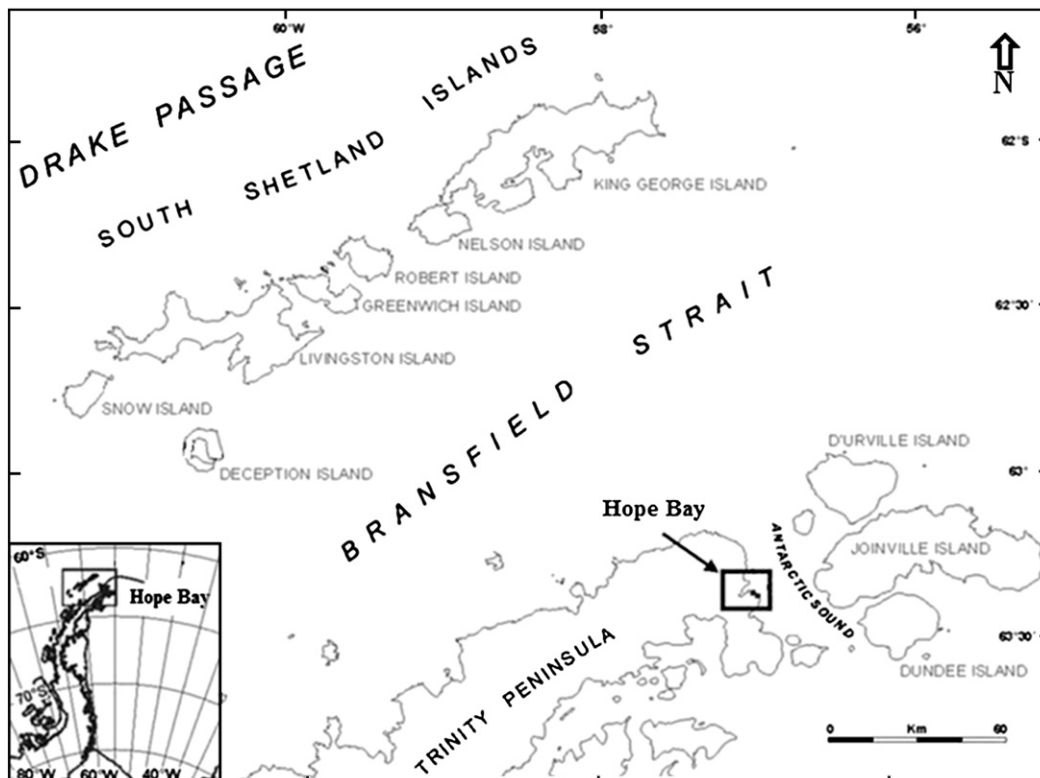


Fig. 1. Hope Bay, Antarctic Peninsula. Adapted from SCAR (2002).

2.3. Micromorphology

Undisturbed soil blocks were sampled at different depths (0–30 cm from the surface). All samples were dried at 50 °C and impregnated with a 1:1 crystic resin:styrene mix poured onto sample at vacuum. Impregnated samples were cut into slabs of 0.5 cm thickness using a diamond saw, and polished with corundum and diamond abrasives from 250 down to 600 mesh. After ultrasonic cleaning, the polished blocks were mounted onto glass slides followed by polishing and hand-finishing to produce 30 µm thick, 10×6 cm sized, thin-sections.

No cover slips were used, and fine ultrapolishing using diamond powder of decreasing size (60 to 1 µm) ensured that a final flat surface was produced. Thin-sections were examined under a Zeiss polarizing microscope (Optic Transmission Microscopy – OTM level) using an attached Pentax camera fitted with a Zeiss exposure meter. Pedological features of the soil horizons at OTM level were analysed using standard micromorphological techniques (Bullock et al., 1985). Selected areas described under the petrographic microscope (OTM) were submitted to SEM/WDS analysis in carbon-coated specimens, at high resolution.

Table 1

Main structural and microstructural characteristics of pedons studied.

Pedon	Classification	Structure ^a	Microstructure ^b	P ^c	Main phosphate minerals (clay fraction)
1	Ornithogenic Haploturbels	w, m, gr	Type: granular (spheroidal peds) Form: equidimensional and triaxial Degree of rounding: rounded Surface roughness: smooth Related distribution pattern ^d : enaulic/gefuric Degree of aggregate development: moderate/strong Pores: complex	6010.6	Taranakite, minyulite, leucophosphate, fluorapatite
3	Ornithogenic Haploturbels	st, m, gr	Type: granular (spheroidal peds) Form: equidimensional and triaxial Degree of rounding: subrounded to rounded Surface roughness: smooth Related distribution pattern ^d : gefuric/chitonic Degree of aggregate development: strong Pores: complex	7149.6	Taranakite
4	Ornithogenic Haploturbels	md/st, m, gr	Type: granular (spheroidal peds) Form: equidimensional Degree of rounding: subrounded to rounded Surface roughness: wavy/smooth Related distribution pattern ^d : chitonic (part porphyric) Degree of aggregate development: strong Pores: complex	7149.6	Taranakite
7	Ornithogenic Haploturbels	md/st, m, gr	Type: granular (spheroidal peds) Form: equidimensional Degree of rounding: subrounded Surface roughness: smooth Related distribution pattern ^d : gefuric Degree of aggregate development: weak/moderate Pores: complex	7237.3	Taranakite, leucophosphate, struvite, fluorapatite
14	Ornithogenic (Anthropic) Haploturbels	w, f, gr./sg	Type: granular (spheroidal peds) Form: equidimensional and triaxial Degree of rounding: subrounded Surface roughness: smooth Related distribution pattern ^d : gefuric (part porphyric) Degree of aggregate development: strong Pores: complex	996.3	Taranakite, minyulite, leucophosphate, struvite, fluorapatite
15	Ornithogenic (Anthropic) Haploturbels	w, f, gr/sg	Type: granular (spheroidal peds) Form: equidimensional and triaxial Degree of rounding: subrounded Surface roughness: smooth Related distribution pattern ^d : gefuric (part porphyric) Degree of aggregate development: moderate Pores: complex	586.4	Taranakite, minyulite, leucophosphate, struvite, fluorapatite
16	Ornithogenic Gelorthents	sg	Type: massive (apedal) or vughy/weakly developed subangular blocky peds Form: equidimensional and triaxial Degree of rounding: subrounded Surface roughness: smooth Related distribution pattern ^d : porphyric Degree of aggregate development: weak Pores: complex	5765.3	Taranakite, minyulite, fluorapatite
17	Ornithogenic Haploturbels	–	Type: granular (spheroidal peds) Form: equidimensional Degree of rounding: subrounded Surface roughness: wavy Related distribution pattern ^d : chitonic Degree of aggregate development: strong Pores: complex	5527.3	Taranakite, leucophosphate, minyulite, struvite, fluorapatite

^a Development: w = weak, md = moderate, st = strong. Size: f = fine, m = medium. Type: gr = granular, sg = single grain.

^b According to Brewer (1964), Stoops and Jongerius (1977), and Bullock et al. (1985).

^c P Mehlich-1 mean.

^d Related distribution pattern follows Stoops and Jongerius (1977).

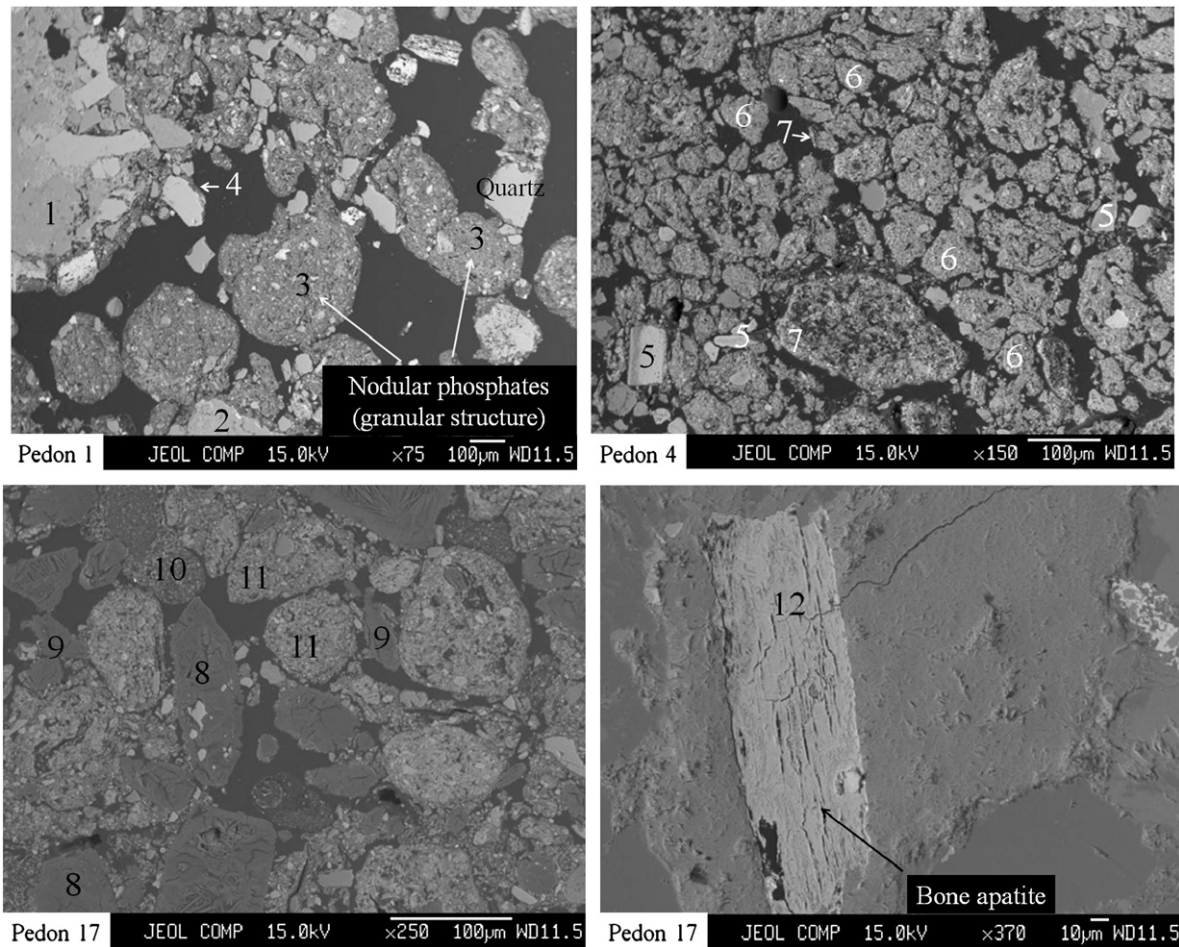


Fig. 2. SEM images showing a well-developed granular structure with compound packing voids and immersed bone apatite fragments observed in different pedons (analyses shown at table 2).

2.4. Sub-microscopy and electron microscopy analysis: SEM/WDS

In all soil thin-sections, the microstructure and sub-microstructure were further investigated using a JEOL 8200 and a Zeiss scanning electron microscopes, both coupled with an Oxford energy dispersive X-ray detector (SEM/WDS), following the recommendations of Bisdorn and Ducloux (1983). Microchemical analyses were acquired at 17 to 18 mm working distance and 15 kV accelerating voltage.

Table 2

WDS analysis of selected micropedological features observed in pedons studied.

Pedofeature	n	CaO %	MgO	Na ₂ O	K ₂ O	SiO ₂	Al ₂ O ₃	P ₂ O ₅	Fe ₂ O ₃	F	Total
<i>Pedon 1 – Ornithogenic Haploturbels</i>											
1 ^a Na-plagioclase	4	0.5±0.1	nd	11.1±0.9	0.4±0.5	69.8±0.8	19.9±0.6	nd	nd	nd	101.8±1.6
2 ^a K-plagioclase	2	nd	nd	0.9±0.7	15.1±1.2	66.9±0.5	17.7±0.2	nd	0.1±0.0	nd	101.8±0.2
3 ^a Fluorapatite	13	45.4±8.9	0.6±0.3	0.8±0.7	nd	nd	nd	18.3±2.9	1.9±0.9	1.4±0.3	68.5±10.4
4 ^a Leucophosphite	4	1.6±1.0	0.2±0.1	0.1±0.1	0.9±0.2	5.2±2.4	5.3±0.5	13.0±1.3	14.1±1.7	0.3±0.2	40.8±2.1
<i>Pedon 4 – Ornithogenic Haploturbels</i>											
5 ^a Na-plagioclase	5	0.8±0.7	0.1±0.1	10.1±2.0	1.2±1.3	66.0±4.5	21.2±1.5	nd	0.1±0.0	nd	99.2±3.9
6 ^a Fluorapatite	17	41.4±5.5	0.4±0.1	0.6±0.2	0.1±0.0	0.9±0.8	1.0±0.3	15.3±2.4	0.4±0.1	1.1±0.2	61.0±7.2
7 ^a Leucophosphite	1	2.7	0.4	0.4	1.1	0.4	1.5	13.4	19.6	nd	39.5
<i>Pedon 17 – Ornithogenic Haploturbels</i>											
8 ^a K-plagioclase	4	0.0±0.0	nd	0.5±0.2	15.7±0.2	67.3±0.7	18.4±0.2	nd	0.0±0.0	nd	102.0±0.7
9 ^a Na-plagioclase	2	0.7±0.2	0.2±0.2	9.3±0.1	1.6±0.4	67.2±0.1	21.8±0.2	nd	0.3±0.1	nd	101.1±0.1
10 ^a Struvite	7	0.8±1.3	21.4±2.0	0.1±0.1	0.0±0.0	0.7±1.6	0.2±0.1	17.4±1.7	0.1±0.0	0.2±0.1	40.9±0.9
11 ^a Taranakite	2	0.3±0.1	0.3±0.1	0.0±0.0	6.5±0.0	0.4±0.1	28.0±1.1	18.6±0.6	0.7±0.1	0.9±0.3	55.8±1.9
12 ^a Bone apatite	10	43.9±5.3	1.5±0.5	0.6±0.3	0.3±0.2	2.7±2.0	2.1±1.4	16.6±1.3	0.8±0.4	1.1±0.3	69.2±5.6

n: number of analysis; nd: not determined.

^a Illustrated in Fig. 2.

3. Results and discussion

All pedons studied represent typical ornithogenic soils from the Antarctic Peninsula. They have a surface accumulation of organic matter derived from guano deposition, under discontinuous mosses and lichens cover, changing abruptly to a mineral phosphatic horizon of bleached colours, and usually cemented. Some characteristics of soils studied are illustrated in Table 1.

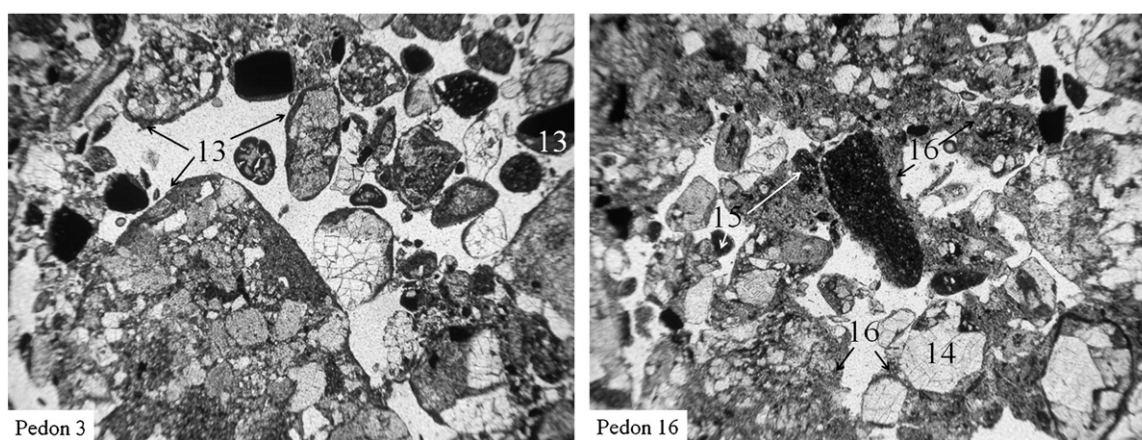


Fig. 3. OTM images of Pedons 3 and 16 showing granular structure in small aggregates. Illuvial deposition of phosphate filling microcracks in the coarse-sized particles (analyses shown at table 3).

Table 3
WDS analysis of micropedological features observed in pedons studied.

Pedofeature	n	CaO	MgO	Na ₂ O	K ₂ O	SiO ₂	Al ₂ O ₃	P ₂ O ₅	Fe ₂ O ₃	F	Total
		%									
<i>Pedon 3 – Ornithogenic Haploturbels</i>											
13 ^a Illuvial phosphate	7	26.2 ± 5.8	1.7 ± 0.3	0.5 ± 0.2	0.4 ± 0.2	4.7 ± 2.1	2.6 ± 1.4	12.0 ± 1.2	1.1 ± 0.8	0.8 ± 0.3	50.2 ± 8.4
<i>Pedon 16 – Ornithogenic Gelorthents</i>											
14 ^a Na-Plagioclase	1	0.2	0.1	5.0	0.2	86.6	8.0	nd	1.8	nd	101.9
15 ^a Fe(OH) ₃ form with P	11	0.8 ± 0.1	0.4 ± 0.0	0.4 ± 0.1	nd	0.8 ± 0.4	1.3 ± 0.6	4.3 ± 0.4	88.3 ± 1.8	nd	96.6 ± 0.9
16 ^a Illuvial phosphate	25	41.4 ± 3.8	0.6 ± 0.1	0.9 ± 0.1	0.3 ± 0.2	1.4 ± 1.0	4.0 ± 0.8	18.0 ± 1.8	2.4 ± 1.3	1.4 ± 0.3	70.7 ± 4.2

n: number of analysis; nd: not determined.

^a Illustrated in Fig. 3.

In general, the soils have a weak to moderate structural development, varying primarily between subangular blocky and granular. Soil microfabrics have a moderate or strong structural development. At this scale, a small to medium-sized granular structure is generally observed, with rounded to subrounded forms, including several well-defined ornithogenic pedofeatures, such as P-rich organic remains, nodular phosphates forms and minute fragments of bone apatite (Fig. 2), with chemical composition presented in Table 2. The microstructure is typically orbicular, ovoidal-shaped, consistent with that described by van Vliet-Lanøe et al. (2004) for cryogenic fabrics of Cryosols from Canada. These materials are usually surrounded by cumulative concentric illuvial deposition of phosphates. van Vliet-Lanøe (1985) and Schaefer et al. (2004) noted that phosphatic coatings on clastic grains, formed as a result of pressured ultra-desiccation of the colloids during the freezing process, which make the granular units resistant to cryoturbation effects, mass wasting stresses, and collapse on thawing.

Fragments of plagioclases and quartz in all soils occur in varying size ranges (< or > 2 mm), indicating the effectiveness of physical weathering and particle size reduction through freeze-and-thawing processes.

The highly diverse size of clasts and grains indicate that soils of this region are formed from extensive mechanical reworking and disintegration. This is expected in this part of Antarctica, as a result of solifluction, cryoturbation and other periglacial process normally occurring in Turbels (Schaefer et al., 2008).

The sub-angular characteristic of sand-sized and coarser particles indicate short-distance transport and physical disruption following thermal microcracking, some with illuvial deposition of phosphates (Fig. 3). The chemical composition of selected pedofeatures is presented in Table 3.

Increasing roundness of lithorelicts with decreasing particle size reflects the effects of differential frost heaving and intense cryoturbation

during freeze-and-thawing cycles, creating ovoidal, granular-shaped, stable peds mostly polygenetic.

At the OTM level, illuvial phosphatic clay occur as bright yellow in-fillings along cleavage lines or broken, cryoturbic fragments of rocks and aggregates, with good orientation (Fig. 4).

The P-rich solution penetrates in cracks and cleavage planes and reacts preferentially with plagioclases forming a framework of phosphatic rims around these materials. According to Schaefer et al. (2008), this reaction with P-rich solutions leads to the progressive displacement of silica from rock minerals, and consequently, enhanced chemical weathering.

Based on microchemistry mapping, the fine material is dominated by phosphatic aggregates (Figs. 5 to 9). In all pedons, phosphatization

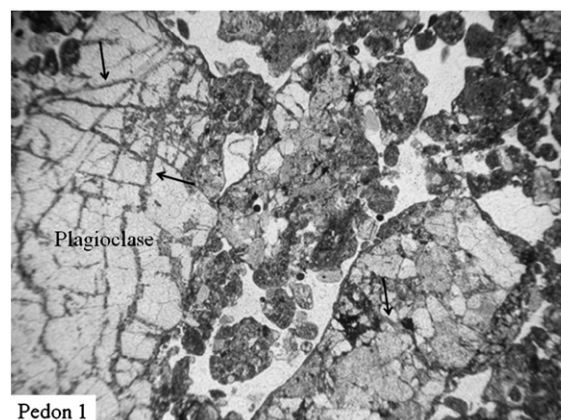


Fig. 4. OTM images showing illuvial phosphatic features in cryoturbic fragments indicated by black arrows. The WDS mean results were 16.8% P₂O₅ for these illuvial phosphates.

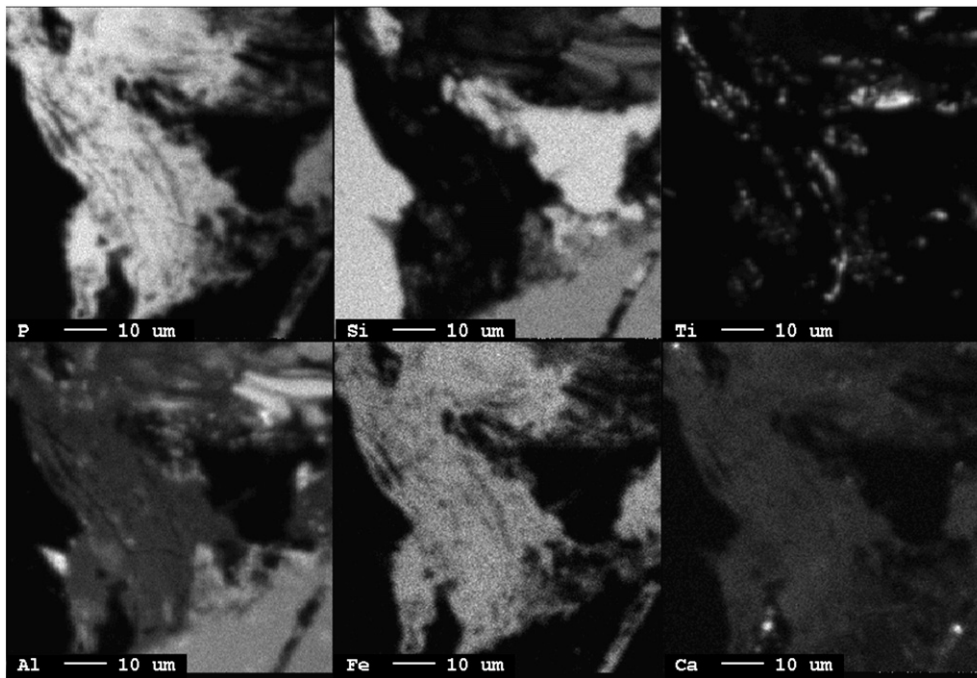


Fig. 5. Qualitative WDS analysis showing phosphatic soil matrix, indicating leucophosphite, fluorapatite, taranakite and minyulite phases (pedon 1).

process occurs throughout, with a combination of P–Al–Fe phases mainly, but also P–Ca or P–Mg.

The chemical composition of the secondary phosphate reflects the nature of the lithofragment that is phosphatized (Table 4). The clasts and grains are composed almost exclusively of plagioclases and quartz, so that Al and Si released from acidolysis. The chemical alteration of the grain leads to P reacting with Al and Fe to form various amorphous and crystalline P phases. According to Blume et al. (2004) and Simas et al. (2006), non-crystalline phases are important soil components and reach >75% of the clay fraction for some ornithogenic soils. Following reaction, the newly formed

aluminium–iron phosphates are concentrated in infillings or as illuvial coating, creating the typical phosphate rich ovoidal aggregates by ultra-desiccation.

Transects analysis were made from the fine soil matrix to the primary Al-silicates that compose the clasts (Figs. 10 and 11). Si and Al peaks increasing intensity indicates the presence of Al-silicates, which may be clays or primary minerals. P reaction with Ca, Fe, Mg and K occurs on the edges or within primary minerals, suggesting that phosphates rich liquid leachates have throughout soaked the clasts in a typical phosphatization process, before were eventually dried-up by freezing and desiccation.

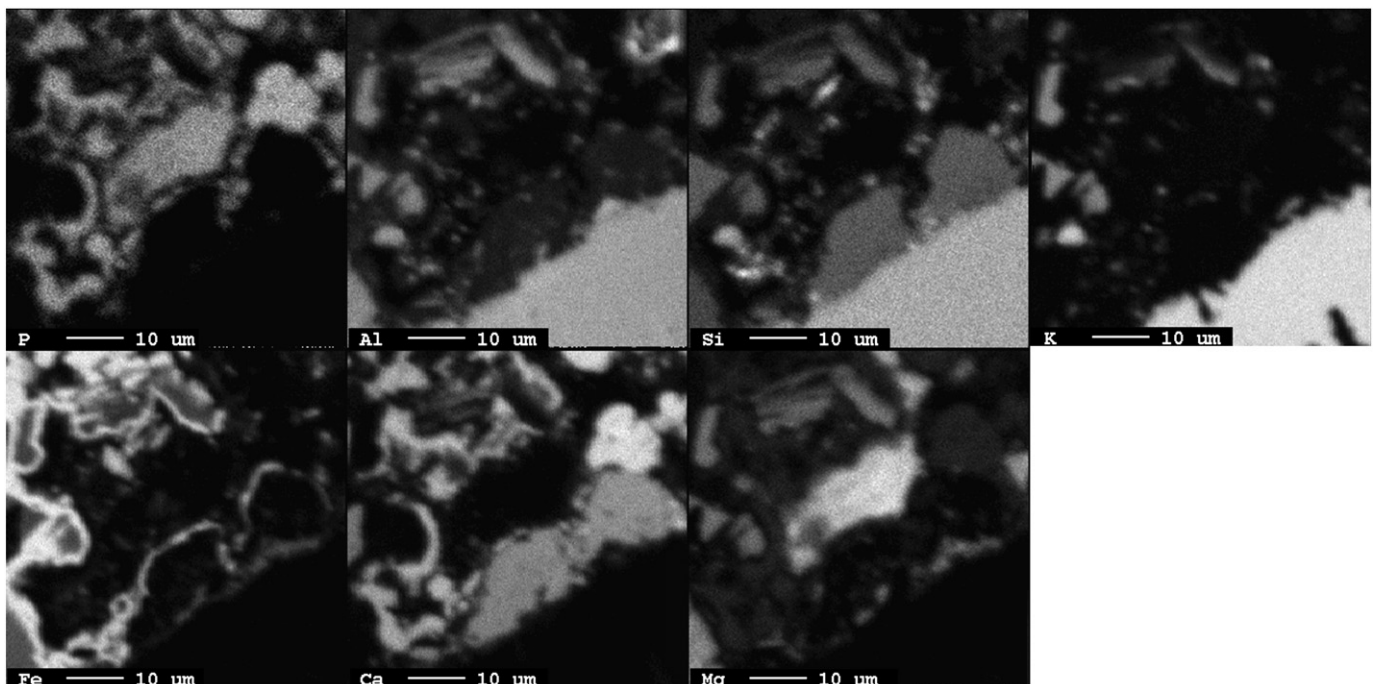


Fig. 6. Qualitative WDS analysis showing phosphatized rock with fluorapatite, struvite, and leucophosphite, based on chemical composition of phosphatic zones (pedon 7/rock).

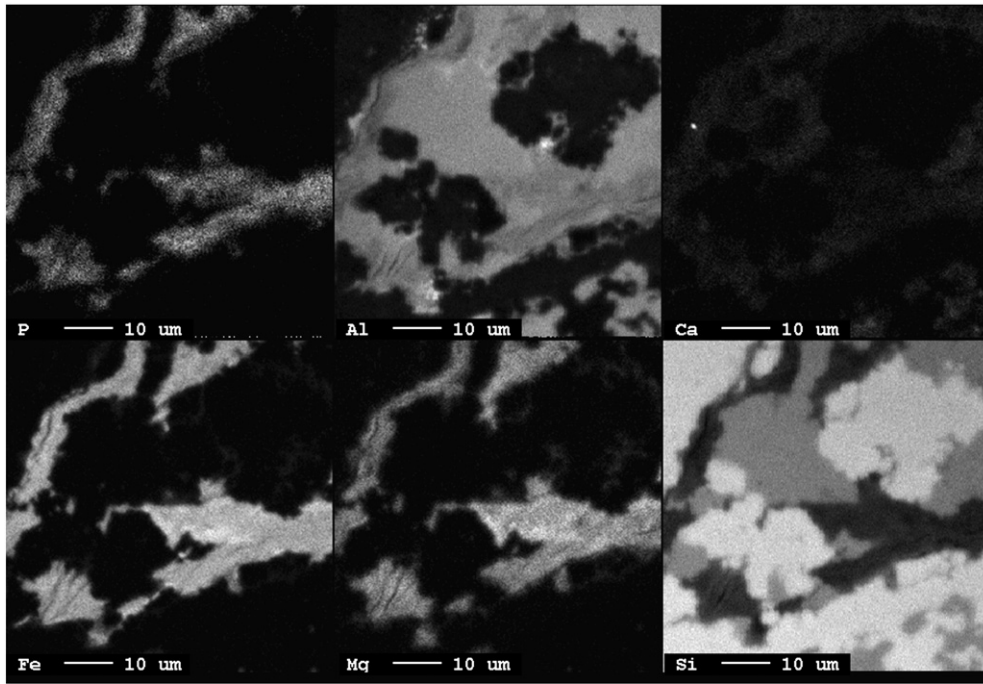


Fig. 7. Qualitative WDS analysis showing microfabric with coatings of taranakite, leucophosphate and struvite (pedon 14).

The chemical composition of some features and X-ray in the clay fraction indicates the presence of discrete forms of taranakite $((K,NH_4)_3Al_5H_6(PO_4)_{8 \times 18}H_2O)$, minyulite $(KAl_2(PO_4)_2(OH,F).4(H_2O))$, leucophosphate $((NH_4,K)_2(Fe,Al)_4(PO_4)_4(OH,F)_2 \times 2H_2O)$, struvite $((NH_4)MgPO_4 \cdot 6(H_2O))$, and fluorapatite $(Ca_5(PO_4)F)$ (Fig. 12), all typical of phosphatization process in ornithogenic soils (Tatur, 1989). However, P and K levels are lower than expected. Concerning the K concentration, Schaefer et al. (2008) indicate that these are degraded phases of these minerals that have lost part of K, and the lower K

amounts may indicate that these minerals contain high proportions of NH_4 in their structures, since N was not analyzed by WDS.

Is notorious in many pedons the affinity between P, Fe and Al (Fig. 10), indicating P-solutions preferably reacts with these elements on the primary mineral surfaces. These may represent very reactive amorphous Fe–Al phases with high P adsorption capacity (Schaefer et al., 2008).

Higher levels of Fe_2O_3 were detected, and pedofeatures were sometimes identified as $Fe(OH)_3$ hydroxides. In Ornithogenic (Anthropic) Haplorturbels, the contents of Fe_2O_3 associated with oxidized debris,

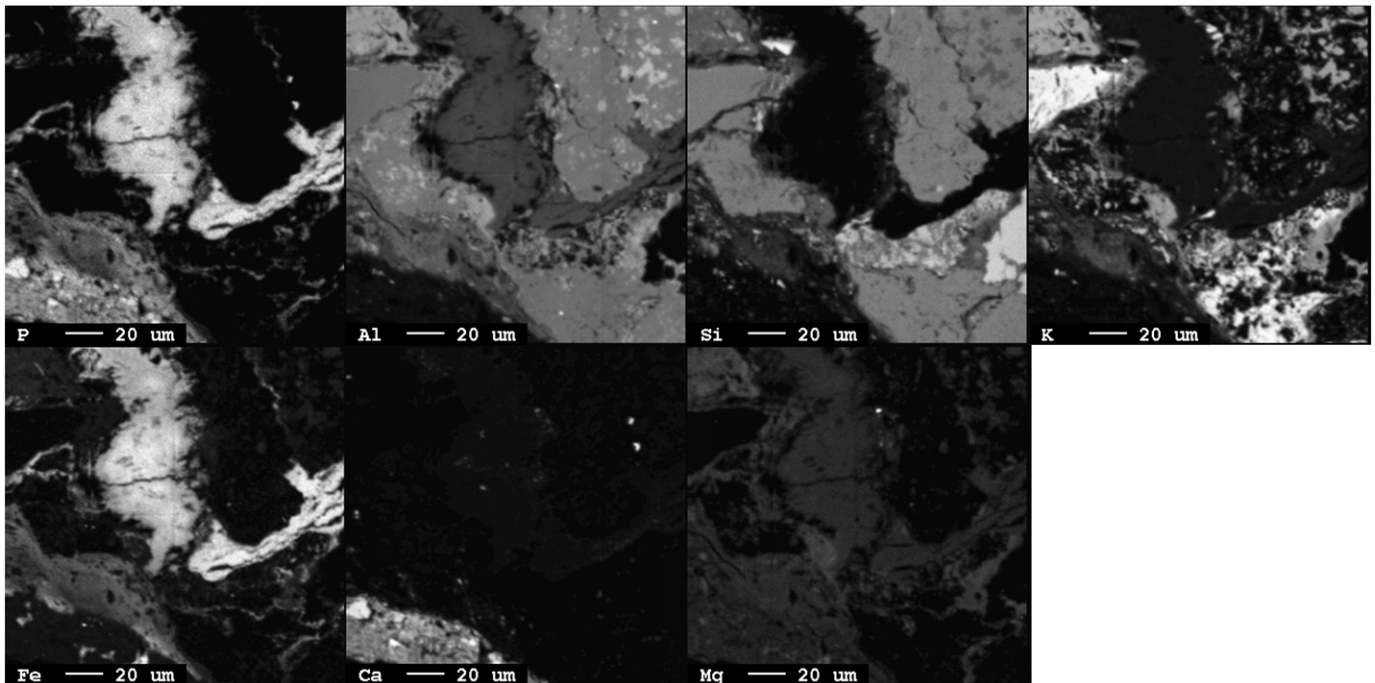


Fig. 8. Qualitative WDS analysis showing clasts filled with leucophosphate (mainly), and fluorapatite, taranakite, minyulite, struvite, based on chemical composition (pedon 17).

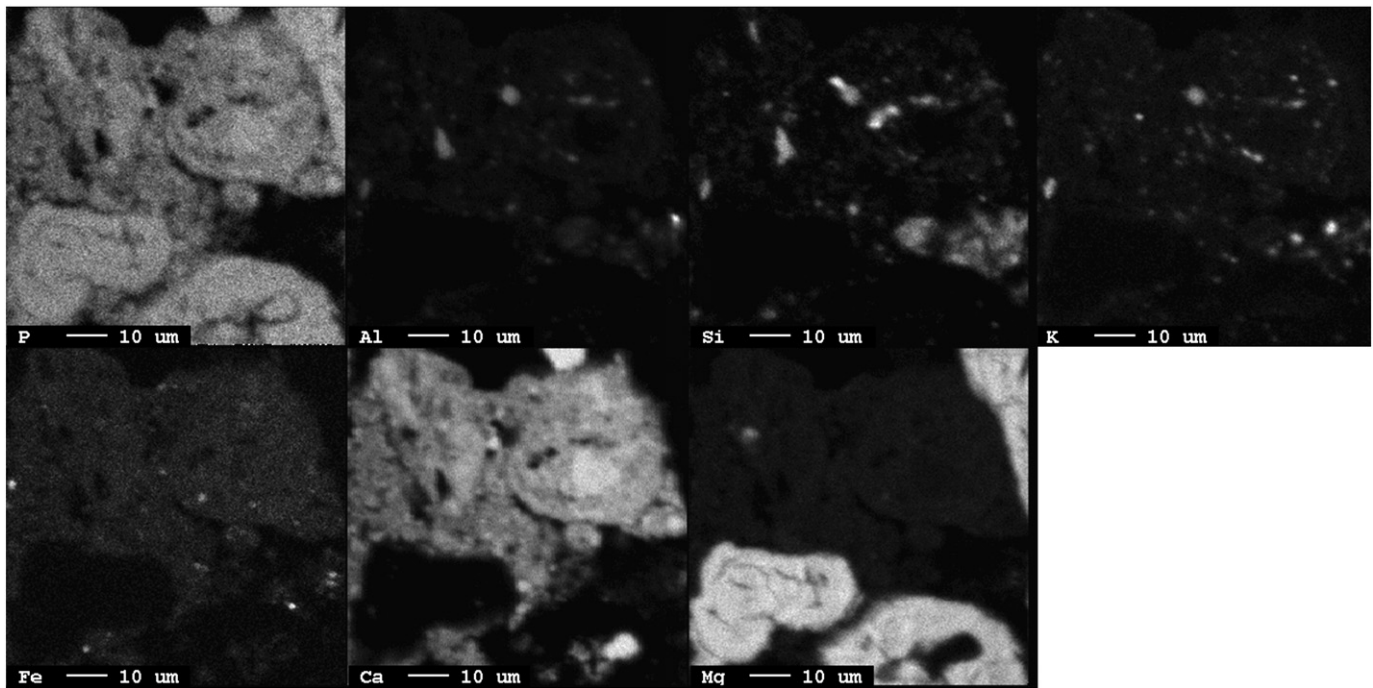


Fig. 9. Qualitative WDS analysis showing subrounded forms of struvite and fluorapatite in pedon 17.

have contributed to the different phosphate forms on the mineral substrate of these sites. In pedon 15 (Table 4), a sequence of WDS analysis in Fe-oxides departing from the soil matrix to the inside of the primary mineral suggests phosphate chemical attack.

Kaolinite, detected by X-ray in the clay fraction treatments (Fig. 13), was not chemically identified by WDS analysis, although some plasma compositions suggest their probable occurrence.

In pedon 14, the detection of illite, precursor of kaolinite, may help to elucidate its existence. Tarnocai and Valentine (1989) showed the presence of kaolinite microaggregates in Cryosols of Canada corresponding to materials formed during warm periods, related to the recently deglaciated areas with evidence of higher chemical weathering. The formation of these minerals in the clay fraction of soils of Hope Bay may be similar.

Table 4
WDS analysis of micropedological features observed in pedons studied.

Pedofeature	n	CaO	MgO	Na ₂ O	K ₂ O	SiO ₂	Al ₂ O ₃	P ₂ O ₅	Fe ₂ O ₃	F	Total
		%									
<i>Pedon 7 – Ornithogenic Haploturbels</i>											
Fluorapatite	1	58.5	nd	0.1	0.0	0.6	0.6	21.7	0.1	1.5	83.1
Al-silicate (P–Fe–K)	1	3.1	5.4	1.3	7.4	34.1	12.1	6.3	9.1	0.1	78.8
<i>Pedon 7/rock fragment</i>											
K-plagioclase	5	0.1±0.1	0.2±0.2	0.5±0.6	15.5±0.7	66.9±0.5	18.5±0.2	nd	0.6±0.3	nd	102.5±0.2
Ca–Na-plagioclase	2	5.2±1.2	0.0±0.0	6.9±2.1	0.2±0.1	68.4±6.1	20.4±4.9	nd	1.0±1.2	nd	102.0±1.4
Na-plagioclase	1	0.5	nd	10.9	0.1	70.0	20.0	nd	0.1	nd	101.6
Al-silicate (Fe–Mg)	3	0.2±0.0	17.2±0.6	0.0±0.0	0.9±0.7	29.9±1.3	19.2±1.9	nd	16.4±1.4	nd	84.8±1.2
Fe(OH) ₃ forms with P	10	1.6±0.3	1.3±0.4	0.4±0.1	0.7±0.5	2.1±0.9	5.1±0.7	3.1±0.3	61.0±2.4	0.1±0.1	75.5±3.0
Fluorapatite	2	53.1±4.8	1.8±1.9	0.7±0.7	0.1	0.3±0.2	0.2±1.2	21.4±0.2	1.1±0.9	0.9±0.0	80.0±2.5
<i>Pedon 14 – Ornithogenic (Anthropic) Haploturbels</i>											
Na-plagioclase (P)	1	0.4	0.4	9.1	0.7	67.0	15.1	0.8	1.0	0.0	94.5
K-plagioclase	1	nd	nd	0.3	15.9	66.8	18.1	nd	0.0	nd	101.2
Illite	3	0.2±0.0	2.8±0.3	0.4±0.6	8.6±0.8	51.4±3.5	26.8±5.0	nd	1.9±0.2	0.0±0.0	92.2±3.2
Fluorapatite	2	56.3±1.5	0.5±0.3	0.2±0.0	nd	nd	nd	21.8±0.1	0.3±0.0	1.4±0.0	80.7±1.1
Fe(OH) ₃ forms with P	2	0.2±0.0	0.1±0.0	0.2±0.2	0.2±0.1	5.7±1.8	1.8±1.0	6.0±2.2	67.7±5.5	nd	81.9±3.7
Al-silicate (P–Fe–Mg)	11	0.4±0.2	6.4±0.6	0.4±0.2	1.4±0.1	32.8±5.5	14.9±0.0	4.1±1.6	14.2±2.0	nd	74.9±0.8
<i>Pedon 15 – Ornithogenic (Anthropic) Haploturbels</i>											
Plagioclase with Fe–Mg	1	8.5	4.8	2.4	2.0	50.9	17.5	nd	10.4	nd	99.0
Ca-plagioclase with Fe	3	22.8±0.4	0.1±0.0	0.0±0.0	0.0±0.1	39.3±0.5	25.0±1.0	nd	9.8±0.4	nd	97.4±1.4
Ca–Na-Plagioclase	3	12.5±2.2	0.1±0.0	4.4±1.3	0.2±0.1	54.4±2.6	29.8±1.8	nd	0.9±0.1	nd	102.4±0.2
Fe(OH) ₃ form*	1	1.4	1.1	0.3	nd	31.8	8.0	1.0	54.6	nd	98.2
Fe(OH) ₃ form**	18	0.2±0.0	0.0±0.0	0.0±0.0	nd	0.2±0.1	0.4±0.2	1.8±0.2	89.5±2.2	nd	92.3±2.3
Fe(OH) ₃ form***	1	0.1	0.0	nd	nd	1.0	nd	0.6	96.9	nd	98.7
Al-silicate (Na–Fe)	2	0.4±0.1	1.3±0.5	4.4±0.9	1.3±0.4	45.3±4.9	11.8±4.7	0.7±0.6	23.0±6.9	0.1±0.0	88.3±4.5

n: number of analysis; nd: not determined. Sequence: *soil matrix near Fe(OH)₃ form; ** Fe(OH)₃ form's edge; ***inside Fe(OH)₃ form.

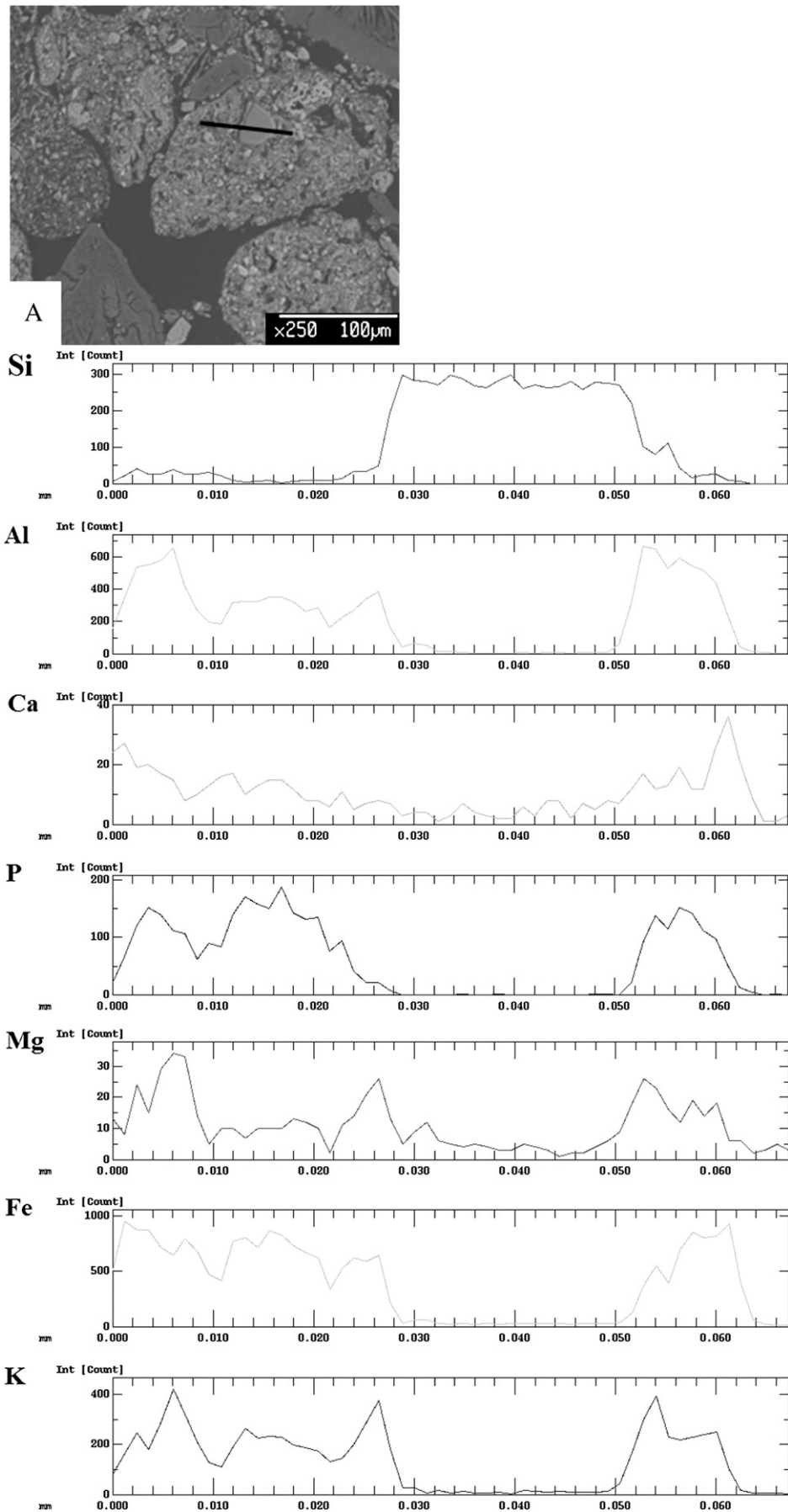


Fig. 10. Transect analysis in microfabric with phosphatic minerals (taranakite, minyulite, struvite, fluorapatite and leucophosphate). P detection at the edges of silicates (comparing P-Si) can indicate reaction due chemical attack (pedon 15). Black line in image A show where transect was performed.

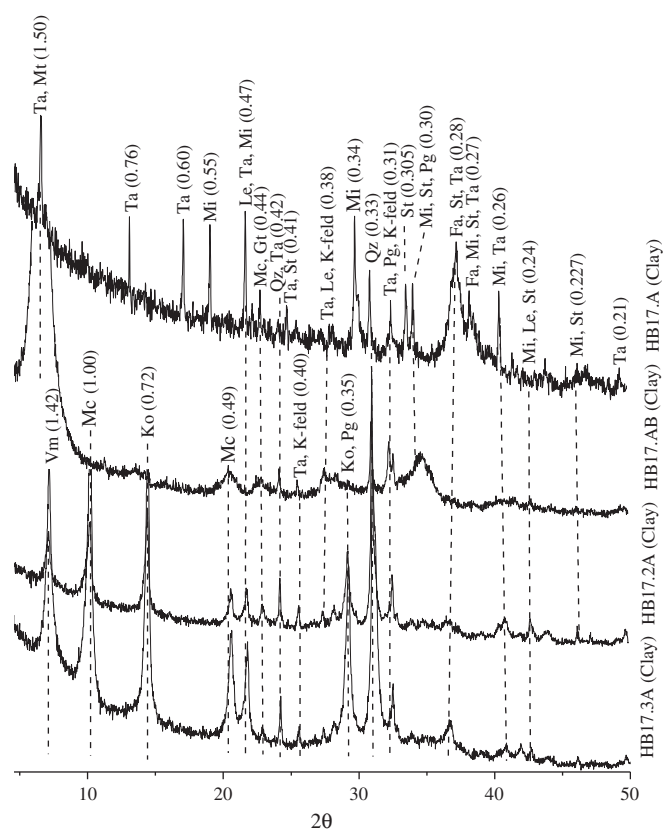


Fig. 12. XRD patterns for the ornithogenic soils at Hope Bay, Antarctic Peninsula. Pedon HB17. Mt – montmorillonite, Vm – vermiculite, Mc – mica, Ta – taranakite, Le – leucophosphate, Mi – minyulite, St – struvite, Fa – fluorapatite, Ko – kaolinite, Gt – goethite, Qz – quartz, K-Feld – K-feldspar, and Pg – plagioclase. “d” in nm.

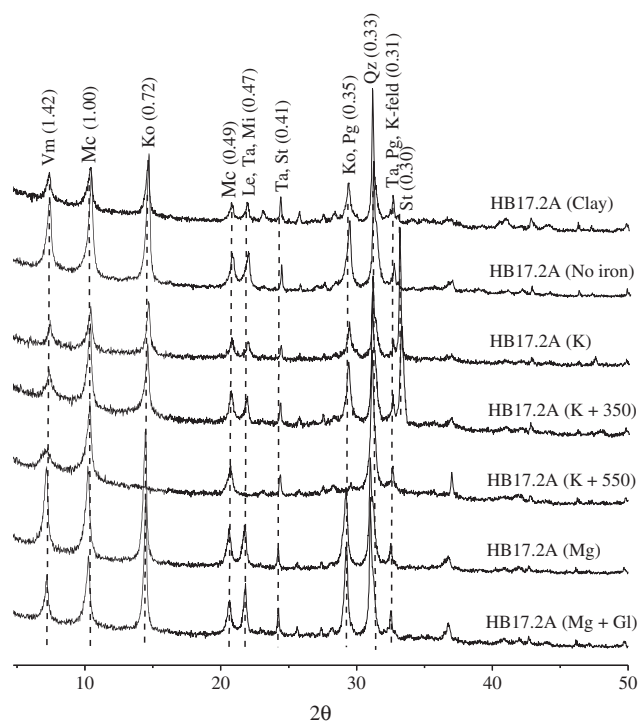


Fig. 13. XRD patterns for the ornithogenic soils at Hope Bay, Antarctic Peninsula (pedon 17 – treatments). Vm – vermiculite, Mc – mica, Ta – taranakite, Le – leucophosphate, Mi – minyulite, St – struvite, Ko – kaolinite, Qz – quartz, K-Feld – K-feldspar, and Pg – plagioclase. “d” in nm.

Another factor which indicates that warmer conditions occurred in the past is the permafrost cementation of deeper phosphate layers. During these warmer periods, P was leached downwards and strongly reacted with the rock substrates.

4. Conclusions

The soils of Antarctic Peninsula have a moderate to strong microstructural development. A small to medium-sized granular structure is generally observed, with rounded to subrounded forms, including several well-defined ornithogenic materials, such as P-rich organic remains, nodular phosphates forms and minute fragments of bone apatite.

The microstructure is typically orbicular, ovoidal-shaped, consistent with that is described for cryogenic fabrics of Antarctic Cryosols from elsewhere. These materials are usually surrounded by concentric illuvial deposition of phosphates indicating a phosphatization soil-forming process.

In the fine matrix, the chemical composition of some sections indicates the presence of discrete phases of taranakite, minyulite, leucophosphate, struvite, and fluorapatite, typical of phosphatization process in ornithogenic soils. In the sand-sized fraction, plagioclases and quartz occur.

Permafrost cementation of deeper phosphate layers indicate that warmer conditions occurred in the past, during which phosphate was leached downwards and reacted with the rock substrates. The occurrence of kaolinite and goethite may be related to these conditions.

The phosphatization process enhances chemical alteration of the substrate and is one of the main soil-forming processes in ornithogenic soils.

Chemical weathering is much more pronounced than previously thought for Antarctic Peninsula, especially for ornithogenic soils under cold climates.

The application of micromorphological and microchemical techniques proved to be extremely useful for a better understanding of pedogenesis in these poorly known Antarctic soils.

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