Micromorphological features of organo-mineral interactions in soils and soil-like bodies of Thala Hills, East Antarctica

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Abstract

Ice-free regions (oases) in East Antarctica have been recognized for their diverse environmental conditions of soil formation. Understanding the biogenic-abiogenic interactions, composition and dynamics of soil organic matter can provide insights into the resilience of Antarctic ecosystems in the face of environmental changes. Therefore, this study is aimed at the investigation of micromorphological features, biogeochemical properties and composition of soil organic matter across various scales in the soil and soil-like bodies of Thala Hills, East Antarctica. The examined soils are typically characterized by shallow profiles, predominantly coarse textures, slightly acidic to nearly neutral pH levels, and very low organic carbon content. Soil horizons studied differed by content of total organic carbon (from 0.42% in the sub-surface horizons to 13.68% in the topsoil Histic horizon in a wind shelter) and nitrogen (from 0.025% to 1.89%). Organo-mineral interactions are primarily observed in the form of biofilms, which predominantly develop in wind-sheltered areas and rock cavities. Micromorphological analyses revealed a predominance of primary materials, which are significantly modified by cryogenic processes (seen by vertical mineral alignment, cracks, and numerous packing voids) and physical weathering, with minimal influence from chemical weathering. Microscopic examination of soil thin sections indicated that the microfabric of these soils is predominantly composed of coarse detrital skeleton with abundant voids, while soils generally exhibit a low proportion of fine earth material.

Key words: cryosols, East Antarctica; micromorphology; organic matter, soil genesis

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Introduction

The interaction between biotic and abiotic processes remains one of the fundamental issues in the study of Antarctic ecosystems, especially in ice-free areas of Eastern Antarctica (Mergelov et al. 2020). Investigation of soil formation in extreme environments of Antarctica allows to delineate the mechanisms of elementary soil processes on the initial stages of such interactions. Antarctica weakly obeys the general geographical law of latitudinal zonality, while ice-free areas are isolated from each other and have no biological or even climatic connection. These areas were partly covered by the continental glacier some 7–9 Kyrs BP (Verkulitch 2009, Verkulitch et al. 2012).

Knowledge on Antarctic soils has been significantly enriched due to fundamental research by Ugolini and co-authors (Ugolini and Bull 1965, Tedrow and Ugolini 1966, Ugolini and Jackson 1982), as well as Bockheim and Hall (2002), Simas el al. (2007), Bockheim and McLeod (2008). Quite significant amount of research projects have been performed in the area of Dry Valleys and Transantarctic Mountains (Ugolini and Bull 1965, Ugolini and Jackson 1982, Campbell et al. 1993, 1998; Bockheim and Hall 2002, Bockheim and McLeod 2008) as well as in various East Antarctica oases. It has been shown that mineral substrate is affected by a sufficient number of pedogenic processes and responding to the impact of the soil-forming factors as the soils of the temperate regions. Such pedogenic processes as desert pavement formation, a redistribution of salts in the profile, *in situ* weathering and deepening of the ice-cemented permafrost as function of time were shown (Ugolini and Bull 1965, Ugolini and Jackson 1982). Numerous research papers are published for the geographical area of Maritime Antarctica, with special attention given to the soils of the South Shetland Islands (Lee et al. 2004, Simas et al. 2007, Abakumov and Alekseev 2018, Lupachev et al. 2020), especially the Fildes Peninsula (Vlasov et al. 2005, Michel et al. 2006, Abakumov 2010).

At the moment only limited number of attempts has been made to combine studies of soil formation processes and detailed microbiological studies (Aislabie et al. 2008, Ganzert et al. 2011, Alekseev and Abakumov 2024). However, these studies mainly concerned the study of specific areas (individual islands and oases). No attempt has been made to combine studies of different geographical and geological areas Antarctica. Still, only few works published have been devoted to identification of the main processes of soil formation in Antarctica. This became especially relevant after the works on soil morphology and micromorphology published by Glazovskaya (1958) and Kubiena (1970), while majority of them were performed in Maritime Antarctica (Glazovskaya 2002, Schaefer et al. 2008, Abakumov 2010, Lupachev et al. 2020). Recent morphological (and micromorphological) soil studies done in East Antarctica focused mainly on the chemistry of soils in Larsemann and Thala Hills (Mergelov 2014, Mergelov et al. 2015). The studies of microbial communities by cultural methods (Lysak et al. 2018) and metagenomics (Alekseev et al. 2020) were related to Larsemann Hills exclusively. Special attention was paid to the study of cryptoendolitic systems (Friedman 1982, Mergelov et al. 2015, 2020). Other studies addressed specific topics such as *e.g.* chemical pollution rates in soils (Kukharchyk et al. 2018, 2024), Eukarya biodiversity in the Thala Hills (Lukashanets et al. 2021), microbial biomass and bacterial filtering forms (Lysak et al. 2018) as well as soil morphological diversity (Dolgikh et al. 2015).

Still, only few studies are available on complex investigation of the micromorphology of permafrost-affected soils of

Antarctica. These studies were mainly conducted in Maritime Antarctica (Schaefer et al. 2008, Pereira et al. 2013, Almeida et al. 2021), while soils of East Antarctic oases have been investigated only sporadically, despite it is of fundamental importance for revealing the information on soil genesis as well as understanding the environmental state in East Antarctic oases. Moreover, this is crucial for ensuring the effective realization of environmental protection measures and saving unique ecosystems under the Antarctic Treaty System.

Our work contributes with the complex investigation of biogeochemical features of initial soil formation in Thala Hills, East Antarctica, interactions with soil microbiota in particular (*see* the objectives below). The work is aimed at the comprehensive investigation of soil micromorphology. The particular objectives were:

- To evaluate main physical-chemical soil properties across landscapes in Thala Hills, East Antarctica;
- To delineate the main features of micromorphological composition and biogenic-abiogenic interactions in thin sections of Cryosols of Thala Hills.

Material and Methods

Study area

Fieldwork and soil sampling for this work have been executed during the 68th (2023) and 69th (2024) Russian Antarctic Expedition in Thala Hills, Enderby Land, which is situated in East Antarctica (Fig. 1). The oasis is described as low altitude, comprised of rounded coastal hills between Freeth and Spooner. The area is hilly with several ridges (10-40 m of relative height). Lakes, snow patches and local glaciers are mostly located in depressions between these ridges. The ridges are usually 1 km long and up to 150 m wide (Dolgikh et al. 2015). Inter-ridge valleys are filled (up to 100-200 meters length) with gravelly silts and moraine or colluvial material as well as the local depressions (from 60 cm to 10-20 meters in diameter).

Thala Hills is underlain by granulite-facies metamorphic and plutonic rocks of the Proterozoic Rayner complex (Black et al. 1987). The oasis is composed of amphibole-pyroxene-plagioclase-quartz feldspar, charnockitized enderbites, amphibole -feldspar-quartz-plagioclase charnockites, and ultrametamorphic feldspar-quartz-plagioclase-amphibole-biotite as well as and Archean biotite-duroxene plagiogneisses, according to Grew (1978).

Climatic features of the area are summarized in Table 1. The area is characterized by strong winds (up to 50 m s^{-1}), average relative humidity is 68%, the average annual temperature is -11°C, the annual precipitation is 250 mm. The local climate of this coastal oasis is more severe compared to the warmer coastal oases of East Antarctica (such as Vestfold and Larsemann Hills). This is due to its small area, elongation in the sublatitudinal direction, and close location to the glacier. Additional water inflow from melting snow patches during the warm season is the most important factor of soil formation. Wind shelters in the rock baths are found as places with the highest biomass formation and accumulation mostly comprising of bryophytes (Mergelov 2014). Another characteristic feature of the oasis is that the local onshore breezes are formed during the summer period as a result of the intensive heating of the exposed rock and soil surfaces (MacNamara 1969).

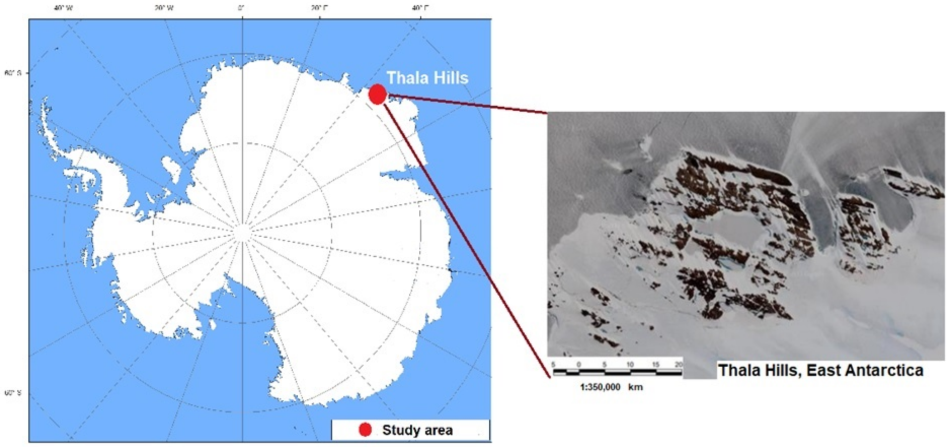


Fig. 1. Area of the study and its location indicated on the map of Antarctica by a red dot. Image Credit ©Google Earth 2010.

Thala Hills				
MAAT (°C)	**MAST (°C)**	**MAGT (°C)**	**Mean annual wind speed (m s^{-1})**	**Annual precipitation (mm)**
-11.0	-8.2	-8.1	10.3	250

Table 1. The main climatic parameters of the study area – Thala Hills, Enderby Land, East Antarctica (data from ROSHYDROMET[1]).

Few studies focused the lichen diversity of Thala Hills (Golubkova et al. 1969, Andreev 1990, 2013). In general, lichen species described in Thala Hills are similar to those of Schirmacher oasis, Bunger Hills, Prince Charles Mountains and other continental coastal regions with some of the species (*Acarospora gwynnii, Buellia frigida, Candelariella flava, Rinodina olivaceobrunnea, Pseudephebe minuscula*) widely known throughout Maritime Antarctica (Øvstedal and Smith 2001). Another study (Lukashanets et al. 2021) reported 51 lichen species, being mostly located in limited areas of the oasis or as individual thalli, mostly in cryptic locations. *Candelariella flava, Xanthoria mawsonii, Rinodina olivaceobrunnea, Amandinea punctata*, *Flavoplaca citrina* were the dominant lichens in moss-algae-lichen associations in wind shelters (such as *e.g.* in Fig. 2), while *Buellia frigida, Umbilicaria decussata, Umbilicaria aprina, Pseudephebe minuscula* were present in wet valleys and under the melting snow patches (Lukashanets et al. 2021). The bryophyte diversity is reported in the studies of Savicz-Lyubitskaya and Smirnova (1972); Kurbatova et al. (2014) with only 9 species detected so far. Western Thala Hills are dominated by *Bryum pseudotriquetrum* and *Ceratodon purpureus*, while the eastern part of the oasis is dominated by *Bryum pseudotriquetrum and Ceratodon purpureus*. In previous research authors performed radiocarbon dating and showed the top layers of peaty soils in Thala Hills are characterized by an $F^{14}C$ of 1.185 ± 0.003; 170 ± 25 BP in sub-surface layer layer and 240 ± 25 BP within the BC horizon (Zazovskaya et al. 2017).

Fig. 2. Locations of Thala Hills with relatively increased moss-algal-lichen diversity. *Left*: wind shelter on a flank of a dry valley, soil – Histic Tuubic Cryosol. *Right*: penguin rookery, soil – Ornithic Cryosol.

Fieldwork has been carried about in accordance to suggestions from ANTPAS Guidebook (Bockheim et al. 2006). In field, soils were classified according to World Reference Base for Soil Resources (IUSS 2022)[2]. Soils were sampled from 20 × 20 cm plots from soil profiles. Collected samples were stored in double sterile plastic bags in the frozen conditions (-10°C), labeled and transported by the research Vessel "Akademik Tryoshnikov" to the laboratory (Arctic and Antarctic Research Institute, Saint Petersburg, Russia).

In laboratory, the samples were first air-dried at room temperature, separated from debris, and passed through a 2 mm plastic sieve before the chemical analysis. The pH values was determined using a pH-meter (soil : solution ratio 1 : 2.5) and particle size distribution were measured using standart pipette-sedimentation method (Kachynskyi 1970). Soil organic carbon content were measured using Vario EL III (Elementar, Germany).

Micromorphological analysis

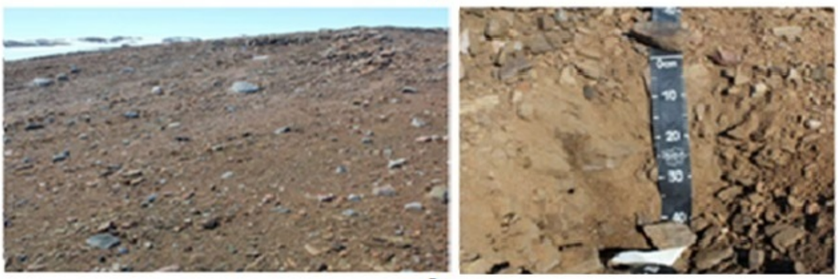
Thin sections of soils were investigated using a polarization microscope Leica DM 750 p in plain and polarized light. For thin sections preparation, samples were air-dried and then saturated with epoxy resin Thin sections were made following the method of Fitzpatrick (1984). Thin sections of soil samples were investigated with 10× – 50× magnification under the transmitted and polarized light. For explanatory text of soil micromorphology, we have used the terminology by Stoops (2003), Gagarina (2004) and Gerasimova et al. (2011).

Results and Discussion

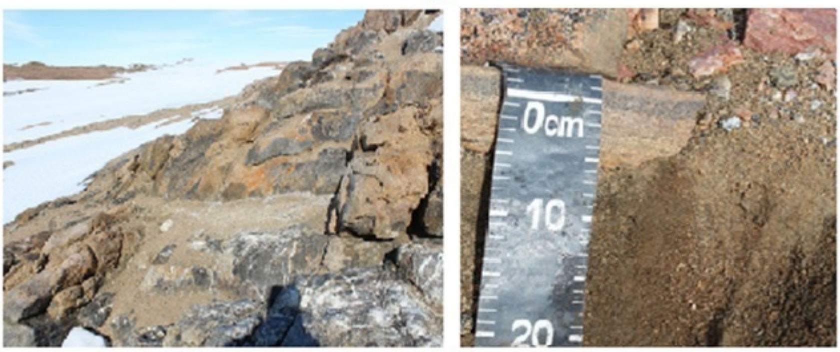
The landscape variability and soil diversity of Thala Hills is presented in Fig. 3. The active layer thickness in both studied oases has been evaluated previously by using vertical electrical resistivity sounding (Alekseev and Abakumov 2020). It ranged between 27 to 106 cm in studied environments of Thala Hills (the highest value here is found at the middle part of well-insolated hill slope and receiving much more water by overlying snow patch), having significant variation due to different landscape positions and amount of liquid water receiving from surrounding snow patches.

We also previously discussed a vital role of gravel pavement to provide more favorable conditions for fine earth formation, accumulation and soil development in harsh environments of East Antarctica (Claridge 1965). Thala Hills, as most of the ice-free areas in East Antarctica, are characterized by extreme climate, which determines the specifics of soil formation – reduced primary production and soil organic matter formation together with prevalence of the biomass under the mineral surface, which greatly changes the vertical organization of the soil profiles.

a



b



c

Fig. 3. Landscape and soil diversity of Thala Hills: a – Turbic Lithic Cryosol (Flank of a dry valley); b – Cryic Turbic Leptosol (High flank of a valley); c – Ornithic Turbic Leptosol (Penguin rookery, initial stage).

Soil physical-chemical parameters

Soil physical-chemical properties of the soils are summarized in Table 2. Both surface and subsurface soil horizons differed in the content of total organic carbon (TOC) and nitrogen (N). TOC values varied in a wide range from 4.20 mg g^{-1} in the sub-surface horizons of ahumic soils to 136.8 mg g^{-1} in the topsoil horizon with Histic features (TO) developed in a wind shelter. High TOC levels, particularly in the surface horizons of Ant1, align with findings by Convey et al. (2014), who noted that surface soils in Antarctica can accumulate substantial organic matter due to limited decomposition rates under cold conditions. Conversely, lower TOC levels at greater depths (*e.g*., Ant2 at 20-35 cm) reflect the reduced accumulation of organic material over time, likely due to slower biological processes. TOC content in Antarctic environments exhibit considerable variability across regions. In the McMurdo Dry Valleys, values range from 0.10 to 2.00 mg g^{-1}, with an average of 0.80 mg g^{-1} (Moorhead et al. 1999). In contrast, significantly higher content has been observed in the lakes of Orkney Island, Maritime Antarctica, where organic C levels span from 24.0 to 120.0 mg g^{-1} (Evans 1982). Northern Victoria Land reports a broader range, with organic carbon content between 0.80 and 30.0 mg g^{-1}, and a mean of approximately 8.0 mg g^{-1} (Cavacini 2001). Meanwhile, soils from Admiralty Bay on King George Island generally contain less than 10.0 mgg^{-1} of TOC (Simas et al. 2007).

The pH values in all studied soils ranged from slightly acidic to almost neutral. These values are consistent with findings from other studies that report Antarctic soils as generally acidic to neutral (pH 4.5 to 7.0) (Bockheim and McLeod 2008). The slightly higher pH values in some samples may be attributed to the presence of carbonate minerals or organic matter decomposition processes that can buffer acidity. The variation in pH across depths and sites suggests localized factors influencing soil chemistry, such as parent material and microbial activity.

In addition, the ratio of carbon to nitrogen (C:N) varies from 5.02 to 13.09. The narrow range observed in the topsoil of Ornithic Cryosol developed under the area of penguin rookery (*Pygoscelis adeliae*) can be explained by the influence of penguin guano, which, in addition to increasing the acidity of topsoils, also leads to increased levels of organic carbon and nitrogen accumulation. It was previously discussed that C:N ratios in Antarctic soils are highly variable, ranging from very low (2–10) in nitrogen-rich ornithogenic soils to extremely high (>50) in barren mineral or polar desert soils with minimal organic input (Simas et al. 2007, Bockheim and McLeod 2008). Maritime Antarctic soils, which are influenced by marine fauna and have higher moisture and biological activity, generally exhibit lower C:N ratios (5–15), while continental Antarctic soils often display values exceeding 40 due to nitrogen limitations and slow organic matter turnover (Aislabie et al. 2008). Nitrogen content is notably low across the samples, ranging from 0.025% to 1.89%. This aligns with previous research indicating that Antarctic soils often exhibit low nutrient availability due to harsh climatic conditions and limited biological activity (Bockheim and McLeod 2008). The low nitrogen levels may also contribute to the observed C:N ratios, which range from approximately 5 to over 13. Higher C:N ratios suggest a predominance of carbon-rich organic materials that are less readily decomposed by soil microorganisms.

Basal respiration values ranged from 0.005 ± 0.001 to 0.123 ± 0.012 mg g^{-1} day^{-1}, which is consistent with the results previously published for skeletal soils of East Antarctica (Abakumov and Mukhametova 2014, Gilichinsky et al. 2010). Higher values of soil respiration were observed in the

Histic horizons as well as on the surface of ornithogenic soil (Ant 7, 0-2 cm). Higher values of basal respiration could be detected in soils under the strong influence of birds, which were previously described for both Western and Eastern Antarctica (Metcheva et al. 2011, Espejo et al. 2017, Santamans et al. 2017). Reported values are also consistent with findings by Abakumov and Mukhametova (2014), who showed low microbial respiration rates in Antarctic soils due to cold temperatures and limited organic substrates. The higher respiration rates observed at shallower depths (Ant1 5-7 cm, Ant 7 2-15 cm) may indicate more active microbial communities where organic matter is more readily available.

Soil ID	**pH_{H2O}**	**pH_{KCl}**	**TOC, $mg\ g^{-1}$**	**N, $mg\ g^{-1}$**	**C:N**	**Basal respiration, $mg\ g^{-1}\ day^{-1}$**	**Fine earth (<2 mm), %**
Ant1 0-5 cm (BC1)	6.67 ± 0.12	6.43 ± 0.15	136.8 ± 10.1	11.6 ± 2.10	11.77 ± 0.94	0.123 ± 0.012	-
Ant1 5-7 cm (BC2)	6.62 ± 0.19	6.34 ± 0.12	21.9 ± 2.10	2.10 ± 0.21	10.33 ± 0.92	0.025 ± 0.008	23.02 ± 0.65
Ant1 7-23 cm (BC3)	6.10 ± 0.28	5.82 ± 0.32	7.5 ± 1.20	0.60 ± 0.10	10.54 ± 0.12	0.009 ± 0.006	20.56 ± 0.77
Ant2 0-5 cm (BC1)	6.42 ± 0.13	5.97 ± 0.12	5.20 ± 0.10	0.490 ± 0.03	10.09 ± 0.21	0.014 ± 0.002	20.03 ± 0.54
Ant2 5-20 cm (BC2)	6.72 ± 0.21	5.97 ± 0.12	4.20 ± 0.20	0.39 ± 003	11.09 ± 0.21	0.008 ± 0.001	18.03 ± 0.55
Ant2 20-35 cm (BC3)	6.82 ± 0.12	6.23 ± 0.10	2.60 ± 0.30	0.25 ± 0.02	10.01 ± 1.21	0.005 ± 0.001	19.01 ± 0.85
Ant 3 0-5 cm (BC1)	6.70 ± 0.11	6.10 ± 0.12	5.70 ± 0.20	0.42 ± 0.03	13.09 ± 0.54	0.014 ± 0.002	20.03 ± 0.54
Ant 3 5-10 cm (BC2)	6.56 ± 0.21	6.12 ± 0.12	4.20 ± 0.20	0.40 ± 0.03	10.01 ± 0.21	0.008 ± 0.001	21.00 ± 0.52
Ant 6 0-3 cm (BC1)	6.10 ± 0.10	5.93 ± 0.12	6.80 ± 0.40	0.56 ± 0.03	11.09 ± 0.54	0.016 ± 0.002	24.03 ± 0.52
Ant 6 3-10 cm (BC2)	6.12 ± 0.21	5.82 ± 0.10	5.60 ± 0.20	0.48 ± 0.03	11.22 ± 0.22	0.009 ± 0.001	21.10 ± 0.45
Ant 7 0-2 cm TOorn	5.30 ± 0.12	4.98 ± 0.12	89.80 ± 8.70	10.89 ± 9.80	5.02 ± 0.87	0.122 ± 0.021	28.02 ± 0.51
Ant 7 2-15 cm (BC)	6.41 ± 0.15	6.09 ± 0.10	9.80 ± 0.80	1.02 ± 0.10	8.98 ± 0.21	0.034 ± 0.008	23.03 ± 0.78

Table 2. Soil physical-chemical parameters in soil horizons of investigated Cryosols in Thala Hills, East Antarctica.

The bulk density of soil horizons increases from the topsoil horizons to the sub-surface horizons. The topsoil of Ornithic Cryosol (Ant 7) is characterized by a lower bulk density (2.23 g cm^{-3}). The fine earth content in studied soils ranged from 18.03 to 28.02%, with the highest values in Ornithic Cryosol. The percentage of fine earth (<2 mm) varies across samples but is notably absent for some entries in the table (*e.g.*, Ant1 at 0-5 cm). Fine earth content is crucial for understanding soil texture and its implications for water retention and nutrient availability (Bockheim and McLeod 2008). The presence of fine particles can enhance soil structure and promote microbial habitats; thus, further investigation into this parameter would be beneficial.

Soil micromorphology

The processes of chemical weathering play a crucial role in the degradation of mineral grains found in the studied Cryosols. The occurrence of kaolinite pseudomorphs after sillimanite further indicates that chemical weathering is actively taking place, a phenomenon that has been previously documented in the context of Maritime Antarctica (Simas et al. 2008, Lopes et al. 2019, Rodrigues et al. 2019). Notably, research conducted by Sedov et al. (2019) and Chen et al. (2000) provides valuable insights into the characteristics of this type weathering in East Antarctic soils and soil-like bodies. Their findings underscore the significance of aggressive acid metabolites derived from organic materials, including moss, lichen residues, and cyanobacteria. These metabolites can lead to substantial mineralogical changes at the microscopic level, particularly within biofilms.

Mineral surfaces colonized by microbial biofilms undergo profound chemical transformations, as these biological layers create highly localized microenvironments that can either enhance or suppress weathering processes (Mergelov 2014). One of the most striking effects of biofilm activity is the dramatic alteration of pH levels in the surrounding soil. In some cases, microbial metabolism drives acidity to extreme lows, with pH values dropping to 3.0–4.0 (Ríos et al. 2003). In other scenarios, particularly where cyanobacterial films are involved, pH levels can swing the other way – rising as high as 9.0 during the dissolution of quartz grains (Brehm et al. 2005).

The micromorphological features of the studied soils reveal a prominent presence of feldspars and quartz (Fig. 4). The impact of cryogenic processes is clearly visible, characterized by vertical mineral alignment, cracks, and numerous packing voids. Furthermore, the effects of physical weathering are markedly evident, resulting in the fragmentation of rocks and extensive mineral fracturing across all analyzed thin sections.

In the studied thin sections, fine earth material is rare and usually present in form of films (brown color) on the sand and gravel surfaces (Fig. 4). Thin sections showed granular and sandy-plasmic matrix together with some zones of clay plasma (features characterizing ferrugination, fluidity and optically oriented clay accumulation, are visible here). This is typical for East Antarctica soils together with clayish films (cutans) on mineral grains of the parent material, which were described previously for various ice-free areas of Antarctica by Lupachev et al. (2020). Other authors who studied thin sections of Cryosols in East Antarctica noticed the predominance of a coarse-grained skeleton and voids in the microstructure in soils and soil-like bodies as well as diffusive character of clay distribution in fine earth (Kubiena 1970, Schaefer et al. 2008).

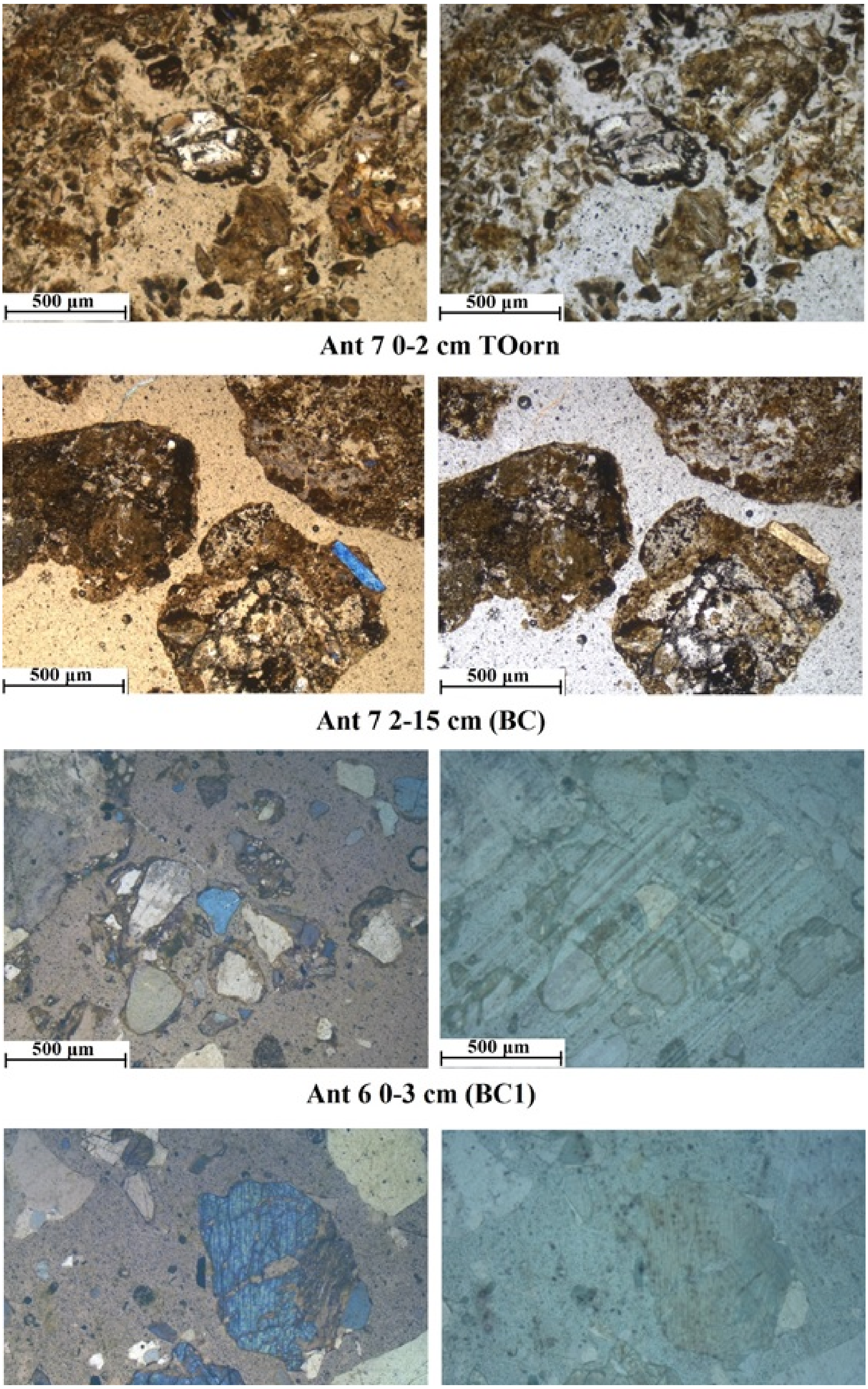


Fig. 4. Micromorphology of studied thin sections: *left* - nicols X, polarized light; *right* - nicols II, plain light. Explanations are given in the text.

Features of sericitization of feldspars were also observed in Turbic Lithic Cryosol, Ant6 3-10 cm sample, Fig. 5. Despite the fact sericitization may have a non-anthropogenic origin, the process has been widely discussed as a possible reason of pedofeature formation in minerals (Konischev and Rogov 2008, Gerasimova et al. 2011).

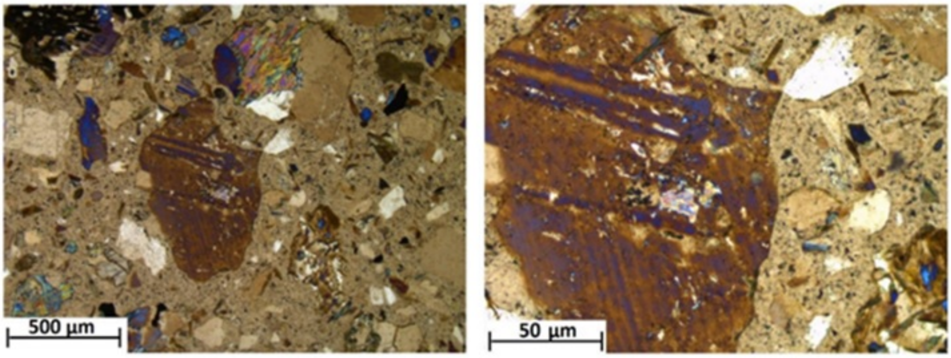


Fig. 5. Sericitization of feldspars in BC horizon (Ant6 3-10 cm) of Turbic Lithic Cryosol.

The soils examined from Thala Hills generally exhibit a low proportion of fine earth material. Typically, thin, sporadic films develop on the surfaces of soil grains; the brown coloration of these films, along with yellowish interference colors observed under crossed nicols – this indicates a predominantly clay-rich composition containing ferruginous elements. Our micromorphological analysis of thin sections largely corresponds with previous comprehensive investigations conducted in other ice-free regions of East Antarctica, such as the Schirmacher Oasis – Sedov et al. (2019); Lupachev et al. (2020) and earlier studies from Bunger Hills and Larsemann Hills (Alekseev and Abakumov 2024). These prior works also noted that most mineral grains possess angular shapes with sharp edges, while their surfaces are marked by numerous cracks and conchoidal fracture patterns–features characteristic of physical weathering driven by freeze-thaw cycles common in polar environments.

In both thin sections analyzed here, fine earth particles are scarce and mostly appear as brown films coating sand and gravel grains (Fig. 4). The microstructure reveals a granular and sandy-plasmic matrix interspersed with localized clay plasma zones. These features reflect processes such as ferrugination, fluidity within the soil matrix, and oriented accumulation of clay minerals – traits typical for East Antarctic soils. Clayish cutans on mineral grains have been documented previously across various Antarctic ice-free sites by Bockheim (2015), Lupachev et al. (2020).

Other researchers studying Cryosol thin sections in East Antarctica have reported a dominance of coarse-grained skeletal material and abundant void spaces within the soil microstructure, alongside a diffuse distribution pattern of clay within the fine earth fraction (Kubiena 1970, Schaefer et al. 2008). The presence of these voids is particularly noteworthy as it signals repeated freeze-thaw activity that shapes soil structure. These voids can enhance water retention and aeration, which are critical for microbial activity in such extreme environments.

Additionally, sericitization of feldspar minerals was observed in the Turbic Lithic Cryosol sample from 3–10 cm depth (Fig. 5). This alteration process transforms feldspars into sericite – a fine-grained mica – which can affect soil texture and nutrient dynamics. Although sericitization may occur naturally without human influence, it has been widely recognized as a key factor in pedofeature development within mineral components (Konischev and Rogov 2008, Gerasimova et al. 2011). These transformations can also modify soil porosity and permeability.

The micromorphological traits identified in these thin sections offer valuable insights into soil formation mechanisms active in East Antarctica. The scarcity of fine earth material suggests that physical weathering predominates over chemical processes in shaping these soils. The presence of thin brown films on sand and gravel surfaces indicates localized accumulation of organic matter or microbial byproducts, which can enhance nutrient availability despite the overall low content of fine earth.

The observed granular and sandy-plasmic matrix points to ongoing pedogenic activity influenced by cryogenic conditions. Zones containing clay plasma imply some degree of clay illuviation facilitated by freeze-thaw cycles promoting particle movement within the profile. This observation aligns with previous findings indicating highly variable clay distribution patterns in polar soils due to dynamic environmental factors (Kubiena 1970, Schaefer et al. 2008). Furthermore, ferrugination features – such as iron oxide formation – highlight the role of chemical weathering formation of these soils. Ferruginous components are integral to biogeochemical cycling in polar ecosystems; they influence not only soil nutrients, but also vegetation distribution across these landscapes (Mergelov et al. 2020). The yellowish interference colors observed under crossed nicols further support this interpretation, suggesting that iron-rich minerals are prevalent.

Recent research has showed the importance of microbial communities in shaping soil micromorphology through bioturbation and organic matter decomposition (Bockheim and Hall 2002). In previous studies of Thala Hills oasis by 16S rRNA metagenomics it was shown that bacteria belong to the phyla Proteobacteria, Actinobacteria, Firmicutes, and Bacteroidetes and the twelve genera *Pseudomonas*, *Shewanella*, *Acinetobacter*, *Sporosarcina*, *Facklamia*, *Carnobacterium*, *Arthrobacter*, *Brachybacterium*, *Micrococcus*, *Agrococcus*, *Leifsonia* and *Flavobacterium* (Akulava et al. 2022). Microbial activity fosters microaggregate formation that improves soil structure and stability. In extreme environments like Antarctica where organic inputs are limited, understanding microbial interactions is crucial for predicting how soils will respond to climate change. The detection of sericitization within feldspars from the Turbic Lithic Cryosol sample points to significant mineral alteration processes occurring naturally but potentially influenced by biological activity. The potential for microbial communities to influence mineral transformations cannot be overlooked; they may play a crucial role in facilitating nutrient cycling and enhancing soil structure.

Overall, Thala Hills soils share common characteristics with other East Antarctic ice-free areas: low fine earth content; thin brown films coating grain surfaces; angular mineral grains exhibiting sharp edges alongside cracked surfaces with conchoidal fractures–all indicative of intense physical weathering driven by freeze-thaw cycles typical for polar climates (Bockheim and McLeod 2008).

Conclusions

This research has generated new insights into the interactions between biotic and abiotic processes in East Antarctica, an area that has been inadequately studied. Understanding these interactions is essential for addressing key questions in ecosystem science and identifying the primary factors that drive soil development under the extreme environmental conditions of Antarctica. Our investigation focused on biogenic-abiogenic interactions within the soils of Thala Hills, previously rarely investigated areas, employing a comprehensive approach that spans from microstructural analysis to assessments at the polypedon level. We utilized advanced instrumental techniques for elemental analysis to elucidate the nature of these interactions, thereby enhancing our understanding of soil formation and development processes in the harsh environment of East Antarctica.

Our findings reveal considerable variability in soil morphological and physicochemical properties across different landscapes within the oasis. Local microclimatic factors – such as the establishment of wind shelters and moisture accumulation in wet valleys – were identified as critical determinants in creating unique conditions that support increased biomass, particularly evident in the extreme climatic conditions of Eastern Antarctica oases, including Thala Hills. Microscopic examination of soil thin sections indicated that the microfabric of these soils is predominantly composed of coarse detrital skeleton with abundant voids, while clay particles are primarily distributed throughout the fine earth in a diffused manner. Despite limited influence from guano deposits in Thala Hills (in comparison to Maritime Antarctica), we found that chemical weathering processes significantly affect soil microstructure alongside prevailing physical weathering.

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