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ORIGINAL ARTICLE

Sediments from cryoconite holes and dirt cones on the surface of Svalbard glaciers: main chemical and physicochemical properties

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Abstract The paper discussed the influence of the forms of sediment accumulation on the surface of glaciers on their chemical and physicochemical properties. The materials sampled from the surface of five glaciers of the Svalbard Archipelago was analyzed. We studied such forms of sediment accumulation as dirt cones - the ice core covered with sediments and cryoconite holes - hollows on the glacier surface containing cryoconite material. Parameters such as total organic carbon content, microbiological activity, pH, the content of mobile forms of potassium and phosphorus, and concentrations of heavy and trace metals were studied. Also, mesomorphological studies were carried out and the polydisperse composition of the sediments was determined. According to the results of this work, it was found that the content of organic carbon in the material selected from dirt cones and cryoconite holes can be up to 2.5%, but the content of clay particles in it is mainly at the 10–15% level. Potassium concentrations are up to 250 mg/kg, and phosphorus is up to 800 mg/kg. The content of metals is typical or lower than in the previously published data. The main influence on the chemical composition of materials has a geographical factor of the sampling site, rather than the form of material accumulation.

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1 Introduction

Glacial sediments of primarily aeolian genesis (cryoconite) are a crucial driver of the microbial diversity of glacial ecosystems and the formation of primary soil cover in post-glacial landscapes (Cook et al. 2016; Crocker and Dickson 1957; Hodson et al. 2008; Mueller et al. 2001; Zawierucha et al. 2015; Zazovskaya et al. 2022). The term "cryoconite" was proposed by the Swedish researcher Nordenskiöld. He named it accumulations of dark material of mainly aeolian genesis that accumulate on the surface of glaciers, the name comes from the Greek *kryos* (cold) and *konis* (dust) (Nordenskjold 1875). Active study of cryoconite began only in the 21st century when researchers have noted several important facts about these natural objects. Accumulation of cryoconite material on the surface of the glacier leads to a decrease in albedo and accelerates the melting of the glacier and deglaciation processes (Ivanov & Svyashchennikov 2015), this phenomenon is characteristic of glacial massifs around the world, such studies have been conducted for glaciers in Antarctica (Bagshaw et al. 2007; Buda et al. 2020; Porazinska et al. 2004), high mountain areas (the Caucasus, Alps) (Abakumov et al. 2021b; Baccolo et al. 2017; Łokas et al. 2018; Zawierucha et al. 2019), the Tibetan Plateau (Dong et al. 2016; Li et al. 2019), glaciers in the Arctic (Greenland, Svalbard Archipelago) (Abakumov et al. 2022; Gribbon 1979, Hodson et al. 2010a; Stibal and Tranter 2007; Zazovskaya et al. 2022) and some other regions. In addition, cryoconite plays an important role in the biological cycle of glacial ecosystems. In places of accumulation of fine particles cryoconite holes are formed, where a specific microclimate is formed, which contributes to the inhabitation of these places by various microorganisms (bacteria and algae) (Anesio et al. 2009; Mueller et al. 2001; Porazinska et al. 2004; Zawierucha et al. 2015). Moreover, particles of cryoconite material can be transported over long distances and can be used to indicate the processes of global migration of pollutants (Abakumov et al. 2022; Kushnov et al. 2021; Łokas et al. 2019; Stubbins et al. 2012).

The accumulation of cryoconite on the glacier surface can implement in different ways, it can be cryoconite holes, and accumulation in various cracks. On the glaciers of Spitsbergen, the amount of cryoconite material is determined by a large flow of dust particles, which are blown down from the mountain ranges and slopes surrounding the glaciers (Belkina & Mavlyudov 2011). With the rapid degradation of a glacier, when its surface is lowered, the layer of cryoconite material can reach tens of centimeters. When a sufficiently thick layer of cryoconite accumulates, the formation of the dirt cones occurs. These are domed or cone-shaped elevations on the surface of the glacier, which are covered by a layer of sediments or cryoconite. They may reach a height of 1–1.5 m and in rare cases even 15–20 m (Kotlyakov et al. 1984, Swithinbank 1950). They are formed as a result of the more rapid melting of pure ice around the area occupied by a thick layer of sediments or cryoconite material (Fig. 1).

The regular, cone-shaped shape of the dirt cones is explained by the constant shattering of material along the edges of the cone during ice melting. Material falls and protects the sides. Prolonged rains and meltwater streams can outwash cryoconite material from the glacier surface. The washed-away material accumulates on the area of the previous glacier position and may further serve as parent material for the primary soils of post-glacial landscapes (Łokas et al. 2017, Zazovskaya et al. 2022).

Cryoconite material plays one of the key roles in the formation of soil cover and biogeochemical processes in postglacial landscapes (Ewertowski 2014; MacDonell & Fitzsimons 2008; Zazovskaya et al. 2022). Some researchers have reported that the transport of cryoconite material from the surface of glaciers enriches moraine material by clay particles, organic carbon, nutrients, and trace elements, and stimulates the growth of biological activity in terrestrial and aquatic ecosystems (Bagshaw et al. 2013; Kushnov et al. 2021; Pereverzev 2012; Zazovskaya et al. 2022). Cryoconite particles enriched with organic matter and populated with microbiota act as parent material for primary soils; this phenomenon has noted for maritime glacial landscapes like those in the Svalbard Archipelago and for retreating glaciers in the South Shetland Islands (Antarctica) (Abakumov et al. 2021b; Crocker and Dickson 1957; Hodson et al. 2008; Hood et al. 2009; Huang et al. 2019; Rozwalak et al. 2022; Stibal et al. 2008).

Thus, the purpose of this work is to determine the physicochemical properties of cryoconite sediments of various forms of accumulation (dirt cones, cryoconite holes, and various moraine and lake deposits in the periglacial zone) from several glaciers of the Svalbard Archipelago. In the cryoconite material, the content of total organic carbon, basic nutrients (available forms of phosphorus and potassium), and a number of metals were assessed. Also, by measuring the CO_2 emission (basal respiration), the level of biological activity in the cryoconite material was determined. It is especially significant as some organic material may come from bird colonies from rocks at the edge of the glaciers. The polydispersity of glacial sediments was evaluated. Statistical processing of the obtained data was performed to compare different forms and accumulation zones of cryoconite on the glaciers of the Svalbard Archipelago.

2 Materials and methods

The study was conducted in the Svalbard archipelago on the island of West Spitsbergen (Fig. 2). The archipelago is located above the Arctic Circle, with a maritime Arctic climate, strongly influenced by the North Atlantic Current. The mean annual temperature on the archipelago is about −6 °C, the mean temperature in July is 8.0 °C, in February −18.0 °C. The sum of year precipitation reaches 560 mm, with the predominance of solid precipitation (Mavlyudov & Kudikov 2018; Zazovskaya et al. 2022; Zinger 2018).

The area covered by glaciers in the archipelago reaches 57% of the total area of the islands (Nuth et al. 2013). The main mass of glaciers is located in the peripheral areas of the archipelago. The central parts of the islands are dominated by small mountain glaciers (Zinger 2018). The glacial cover of the archipelago is rapidly degrading. Since the 1920s, there has been deglaciation of glaciers on Nordenskiold Land, Dickson Land, and Prins Karls Land (Chernov and Muraviev 2018; Ewertowski 2014). Over the past few decades, the Austre Grønfjord and Aldegonda glaciers have significantly decreased and continue to degrade (Elagina et al. 2021; Mavlyudov & Kudikov 2018). The Aldegonda Glacier is rapidly shrinking at present; according to recent estimates, most of the glaciers may completely disappear in 40–50 years (Mavlyudov & Kudikov 2018).

In September 2021 (07.09–15.09), 38 samples of glacial material (cryoconite) with different genesis and different types of accumulation were collected in 5 reference zones. The sampling strategy was as follows: from the 38 samples, 22 samples were collected from glacial dirt cones, 11

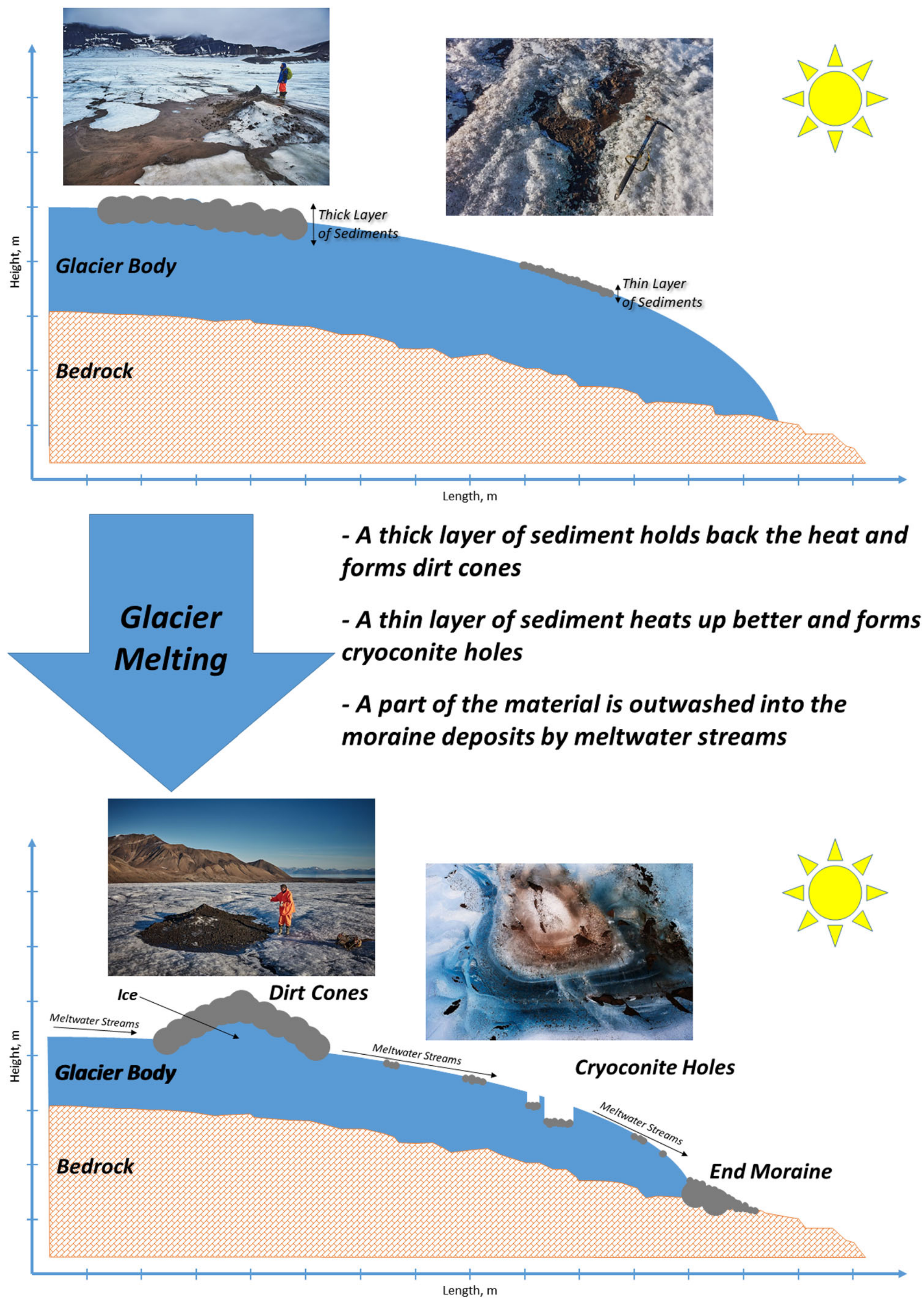

Fig. 1 Transfer of cryoconite material across the surface of glaciers and the formation of glacial relief (Photos by Mavlyudov, 09.2021)

samples from cryoconite holes, and 5 samples of various moraine and lake deposits from the periglacial zone. As a result of the field work, samples were obtained from three different forms of accumulation of cryoconite material on the glacier surface: (1) dirt cones; (2) cryoconite holes; (3) lake and moraine deposits (hereinafter referred to as others).

After collection, samples of glacial sediments (cryoconite) were placed in sterile plastic bags and transported to the Russian Research Center on Spitsbergen, where they were air-dried at 30 °C. After drying, the samples were transported to the Department of Applied Ecology at St. Petersburg State University for further analysis. Before beginning laboratory studies, the samples were cleaned of large organic residues and sifted through a sieve with a mesh diameter of 2 mm.

The pH values were determined using the pH/ORP/Temperature Portable Meter Milwaukee Mi 106 (Romania) potentiometric method (FAO 2021a). The total organic carbon (TOC) content was determined by the Tyurin

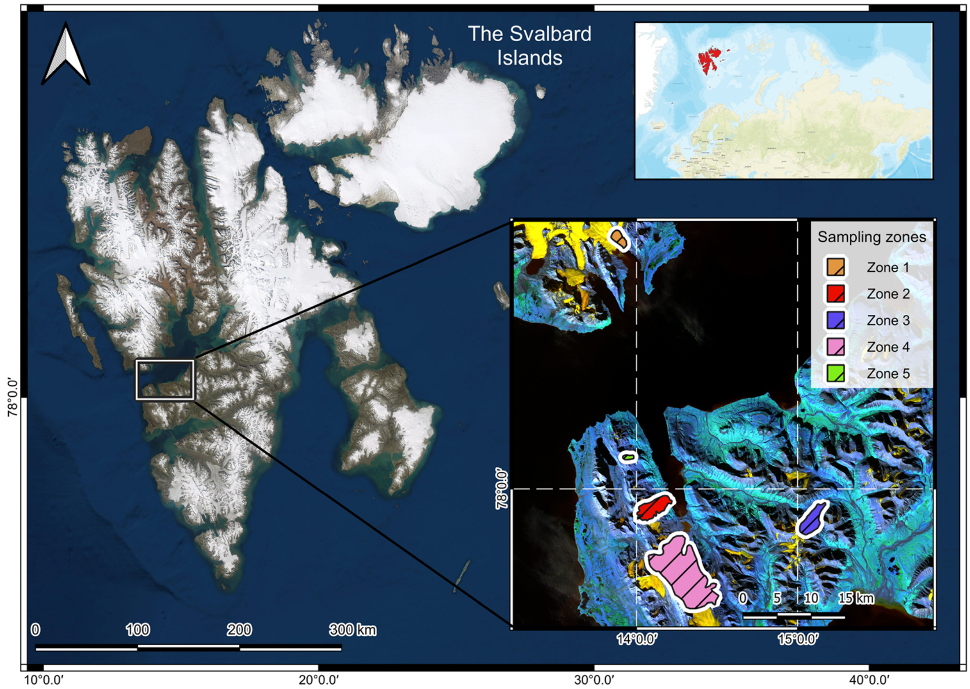

Fig. 2 Sampling location. Zone 1—Esmark Glacier, Zone 2—Aldegonda Glacier, Zone 3—Tavle Glacier, Zone 4—West and East Grønfjord glaciers, Zone 5—Vøring Glacier. Satellite image of the Sentinel-2 mission (28.08. 2021), channel combination 4-8-11

method by oxidation of organic carbon with a solution of potassium dichromate and concentrated sulfuric acid (FAO 2021b). Basal respiration was determined by closed cell method by capturing carbon dioxide emission from samples with 1 N sodium hydroxide solution followed by titration with 0.5 N hydrochloric acid solution in the presence of phenolphthalein and bromocresol indicators (Jenkinson & Powlson 1976). The particle size distribution of the samples was determined by sedimentation with preliminary peptization of the samples with 4% sodium pyrophosphate solution (Kroetsch & Wang 2008). Concentrations of mobile forms of phosphorus and potassium were determined by colorimetric methods, phosphorus—on spectrophotometer PE-5300v (Russia), and potassium – on flame photometer Jenway PFP7 (UK). Extraction of mobile forms of potassium and phosphorus was carried out by 0.2 N hydrochloric acid solution (GOST 2019). Concentrations of heavy metals were determined by atomic-absorption and atomic-emission methods on Kvant-2 M spectrometer (Russia). Extraction of metals was carried out with 1 N nitric acid solution (ISO 1998). Mesomorphological studies were performed using a Webbers F2CN Digital Microscope (magnification x10-x200). Laboratory measurements were carried out in triplicate for each sample, and all equipment has the appropriate quality certificates and has been verified by means of standard samples (measurements of compounds concentrations in standard samples are given in the Supplementary files).

The following software was used for visualization and statistical data processing: MS PowerPoint 2016, QGIS v3.16, Statistica v12.0, GraphPad Prizm v9.0.0, Golden Software Grapher v13. We also used Sentinel-2 satellite images for 28.08.2021 downloaded from the United States Geological Survey website (https://earthexplorer.usgs.gov/).

3 Results and discussion

3.1 Polydispersity of cryoconite material

The cryoconite material has a granular mesomorphological organization. Granules up to 3 mm in diameter are formed in cryoconite holes and on the surface of dirt cones (Fig. 3). These granules are particles of quartz sand, which are glued with dark-colored organic matter. The main source of organic matter in glacial ecosystems are various species of algae, cyanobacteria, and other microorganisms (autotrophic, heterotrophic, and photosynthetic) (Hodson et al. 2010b; Langford 2012; Langford et al. 2010; Uetake et al. 2016).

After sieving the samples and additional grinding in a porcelain mortar, the granules were separated and the particle size distribution of the cryoconite material was determined. As can be seen from Fig. 4, the particle size distribution of cryoconite is mainly represented by the silty (0.001–0.05 mm) and sandy (0.05–1 mm) fractions. The content of clay particles (< 0.001 mm) is mainly in the range of 5 to 12%. Only in two samples the amount of clay particles exceeds 20%.

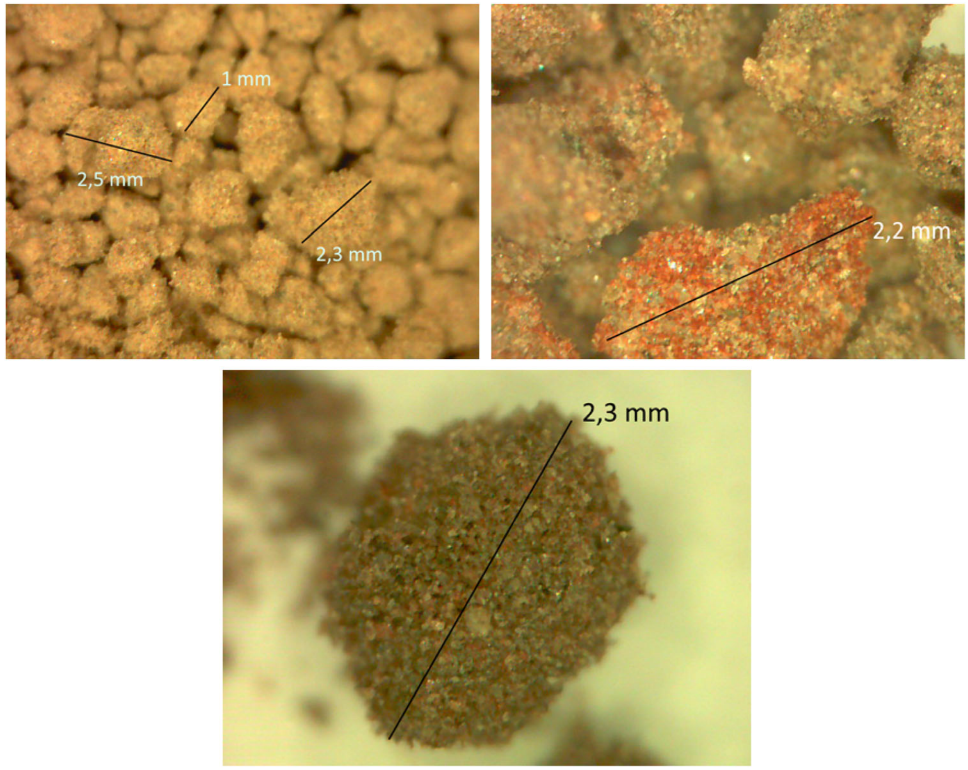

Fig. 3 Mesomorphological structure of cryoconite material (The picture was taken after the sample had air dried)

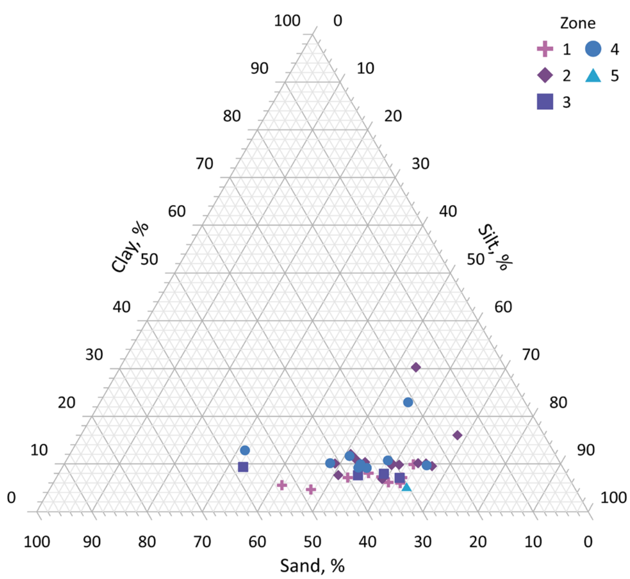

Fig. 4 Particle size distribution of cryoconite material

The polydisperse composition of cryoconite sediments depends on the bedrock underlying the glacier, the degree of erosion of nearby landscape elements, and the processes associated with the chemical and physical weathering of previously accumulated sediments. Usually, cryoconite material consists mainly of mineral components (up to 95%). The remaining part is occupied by thin fractions consisting of dead or living organic matter (Abakumov et al. 2021a, Cook et al. 2016, Edwards et al. 2014).

To statistically (analysis of variance (ANOVA) was conducted by categorizing factors: 1, forms of material accumulation, 2, sampling zones of cryoconite) testing the differences in the particle size distribution of the material between the form of its accumulation and the sampling areas, the parameter of the number of clay particles was selected. As can be seen in Fig. 5, no statistically significant differences between these two factors were found (at confidence level $p = 0.05$).

3.2 Total organic carbon and main nutrients content, pH value, and basal respiration rate

Cryoconite material is constantly under the influence of glacial meltwater and is usually not characterized by a strongly acidic or strongly alkaline pH. Typically, the pH values in the cryoconite holes and the material itself range from slightly acidic to slightly alkaline. For example, cryoconite material from glaciers in the vicinity of Ny-Ålesund in northwest Spitsbergen is characterized by pH values of about 6 (Kaštovská et al. 2005). At the Midre Lovénbreen glacier, cryoconite sediment pH values up to 8.6 (Singh & Singh 2012). It was noted earlier that in the cryoconite holes on the glaciers of Spitsbergen microbiological activity can proceed in a wide range of pH and the

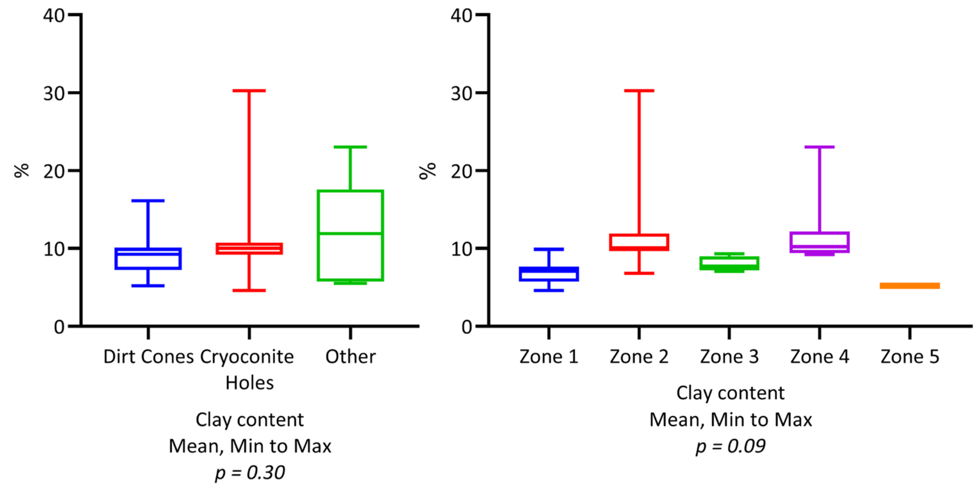

Fig. 5 Content of clay particles in different forms of accumulation and sampling areas

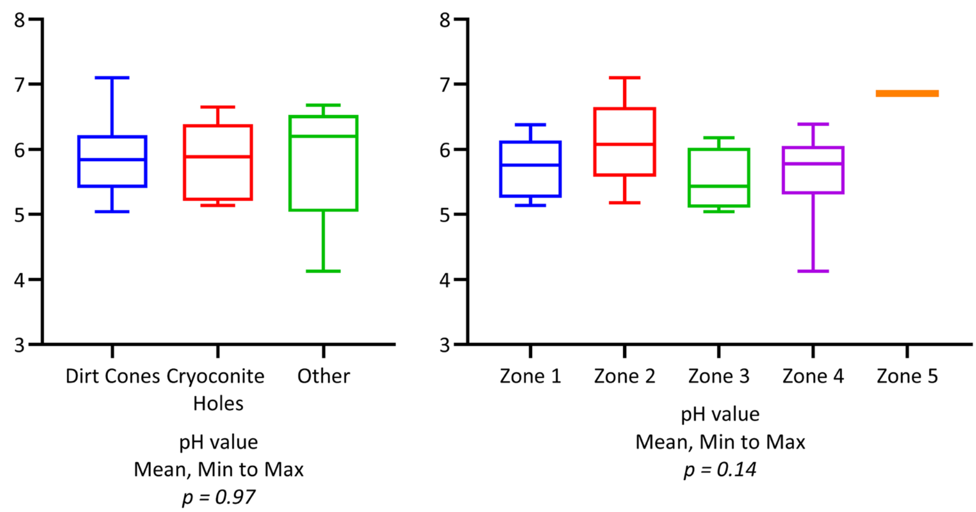

Fig. 6 pH value in different forms of accumulation of cryoconite material and sampling areas

microorganisms living there have a high level of tolerance to the reaction of the environment (Poniecka et al. 2020).

The samples of cryoconite material from cryoconite holes and dirt cones that we studied are characterized by a tighter range of pH values compared to the lake and bottom sediments and soils (Fig. 6). The lowest pH = 4.1 values were recorded for lake sediments near the Grönfjord glacier (zone 4). The highest pH = 7.1 values were found for the material from the dirt cone on the Aldegonda glacier (zone 2). No statistically significant differences in pH values between different forms of cryoconite accumulation and sampling areas were found.

The basal respiration rate allows us to estimate the primary biological activity in soils and cryoconite material (Kaštovská et al. 2005; Kushnov et al. 2021; Telling et al. 2012). Measurement of CO_2 emission from cryoconite material under laboratory conditions showed that the respiratory activity of microorganisms varies depending on the sampling site of the cryoconite material (sampling zone factor), but not on the form of accumulation of this material (Fig. 7).

Microorganisms are able to release up to 100 mg of carbon dioxide from 100 g of sample per day (cryoconite sample from dirt cones from the Esmark Glacier). Respiration levels did not fall below 20 mg CO_2 per 100 g sample per day in any of the samples, indicating the presence of microbiota in all selected samples of cryoconite material.

The content of total organic carbon in the samples of cryoconite material we studied from different forms of accumulation and sampling zones varies from 0.35% [point 4, material taken from an outwashed spot of cryoconite on the Grønfjord Glacier (zone 4)] to 2.5% [point 16, material taken from the dirt cone on the Aldegonda Glacier (zone 2)]. The average carbon content (n = 38) is 1.12%. The spatial distribution of the carbon content is shown in Fig. 8. The figure clearly shows that the maximum carbon content often falls on the material sampled from the margins of the glaciers close to the end moraines (points 15, 16, 34, 23).

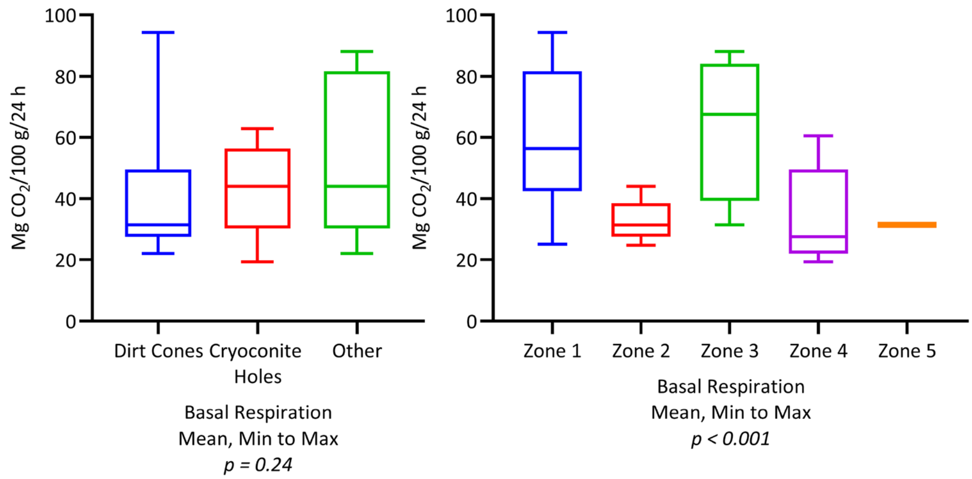

Fig. 7 Basal respiration rate

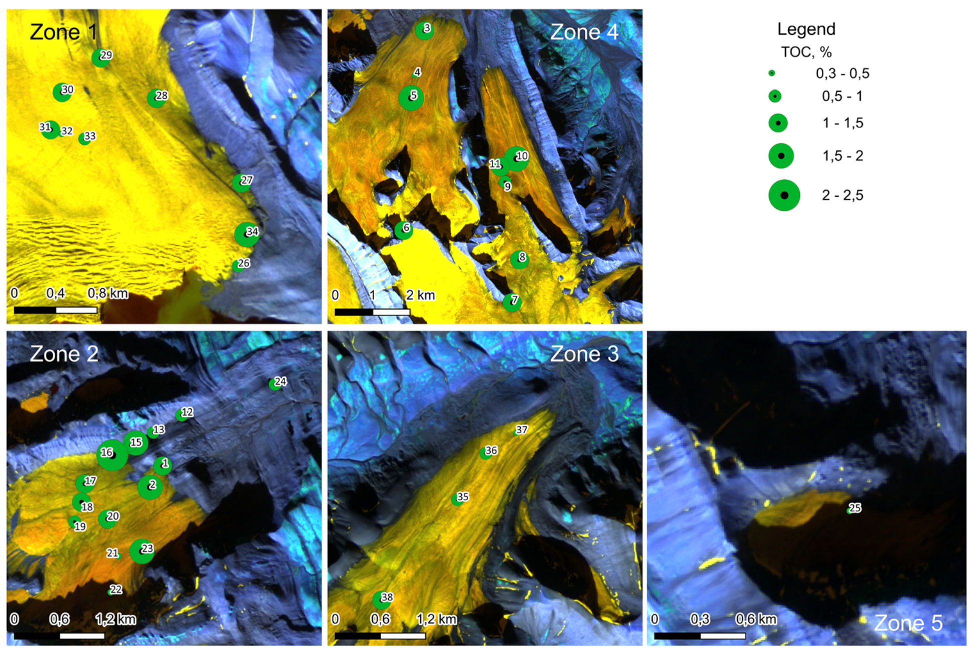

Fig. 8 Total organic carbon (TOC) content, %

No statistically significant differences in carbon content between the cryoconite material from different forms of its accumulation and sampling areas were found (Fig. 9). Previous studies for cryoconites from the Aldegonda Glacier revealed that the genesis of organic carbon in the cryoconite material is heterogeneous, as carbon can enter supraglacial ecosystems from different sources (Zazovskaya et al. 2022). It can be a transfer from remote areas, as well as the production of organic matter by microorganisms in situ. Scenarios of carbon introduction by ornithofauna and melting of older sediment layers from deep layers of glaciers with a negative mass-balance are also possible (Nizamutdinov et al. 2022; Polyakov et al. 2020; Stibal and Tranter 2007; Telling et al. 2012; Zazovskaya et al. 2022).

Cryoconite material plays an important and crucial role in the biogeochemical cycle of carbon, nitrogen, and nutrients in glacial and supraglacial ecosystems (Cameron et al. 2012; Hodson et al. 2010b; Langford et al. 2010; Nizamutdinov et al. 2022; Telling et al. 2014; Telling et al. 2012). In this study, we measured concentrations of two major nutrients, mobile forms of phosphorus and potassium, in samples of cryoconite. As can be seen from Fig. 10, the concentration of mobile phosphorus can reach 800 mg/kg (point 25, material from dirt cone of cryoconite from Zone 5). The minimum phosphorus content (14.9 mg/kg) was found in point 37 (material from the cryoconite dirt cone in Zone 3). The average content of mobile phosphorus (n = 38) is 377.2 mg/kg.

Phosphorus in the cryoconite material can flow from various sources. The first source is the chemical weathering

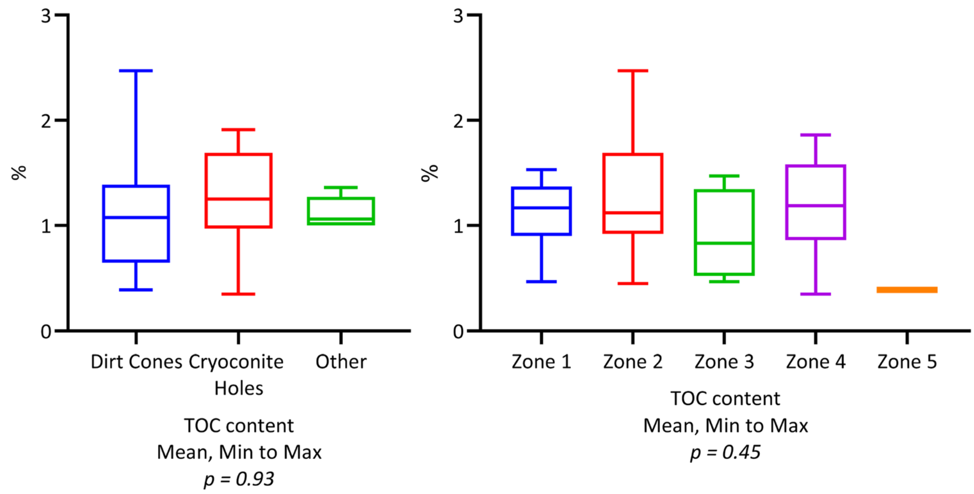

Fig. 9 TOC content in different forms of accumulation of cryoconite material and sampling areas

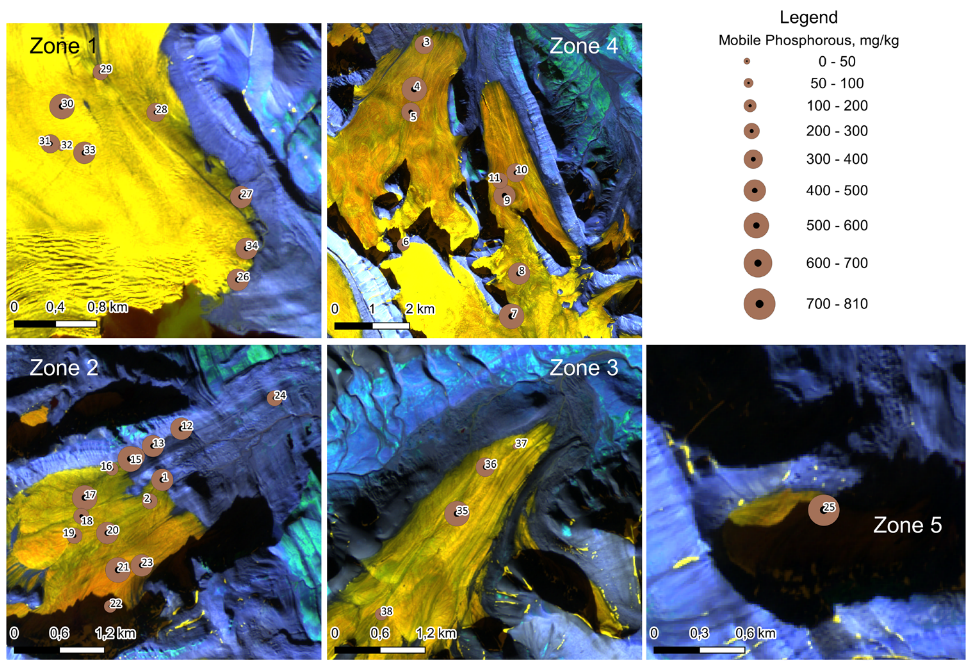

Fig. 10 Mobile phosphorous content, mg/kg

of minerals such as apatite (Stibal and Tranter 2007). These forms of phosphate are converted into mobile forms by various phosphotrophic microorganisms (Bagshaw et al. 2013; Säwström et al. 2002; Schmidt et al. 2022). In polar ecosystems, phosphorus also moves into the ornithogenic transport of matter (guano). Some researchers have noted an extremely high content of phosphates in ornithogenic soils and cryoconite sediments in Antarctica (Abakumov et al. 2021c; Nizamutdinov et al. 2022; Rodrigues et al. 2021; Zharikova 2020).

However, there were no statistically significant differences in the content of mobile phosphorus between forms of accumulation of cryoconite material and sampling zones (Fig. 11).

The source of potassium in glacial ecosystems and subglacial soils is the product of chemical and physical weathering of potassium-bearing feldspars (microcline, orthoclase) (Breen & Lévesque 2008; Nagatsuka et al. 2014; Prestrud Anderson et al. 1997). Cryoconite sediments can also be enriched in potassium due to aeolian mass transfer of mineral particles over long distances and their sedimentation on the surface of glaciers. Understanding the potassium content is important for understanding the effect of washed out cryoconite material on the fertile qualities of soils developing on postglacial deposits.

The content of mobile potassium in the cryoconite material varies over a wide range (Fig. 12). The minimum concentration of 1.6 mg/kg was recorded at point 37

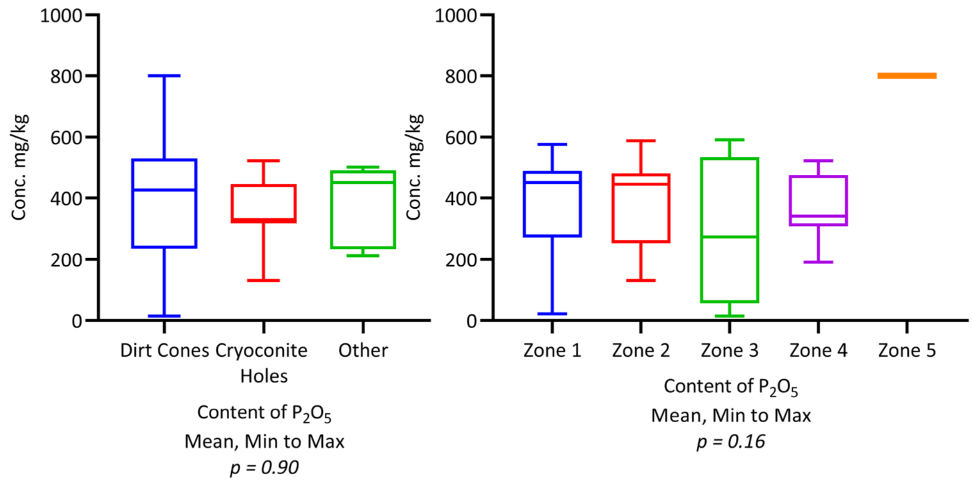

Fig. 11 Mobile phosphorous content in different forms of accumulation of cryoconite material and sampling areas

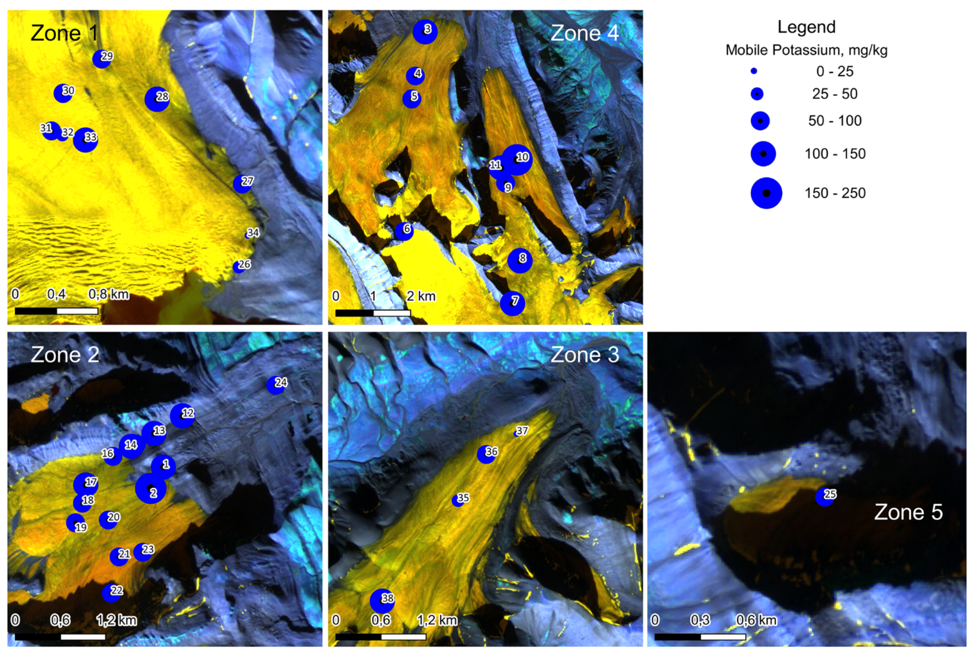

Fig. 12 Mobile potassium content, mg/kg

[material from the dirt cone cryoconite sampled at the Tavle Glacier (Zone 3)]. The maximum concentration of 232.7 mg/kg was recorded at point 2 (material from the cryoconite hole on the Aldegonda Glacier (zone 2). The average concentration of mobile potassium ($n = 38$) is 87.7 mg/kg. As can be seen from the maps of spatial distribution any dependence is not traced, spots of high concentrations are distributed chaotically and most likely depend on the degree of drainage and water regime in a particular sampling point.

Statistically significant differences between the form of accumulation of cryoconite material and the sampling location were not revealed (Fig. 13).

3.3 Trace elements and metals content

On the territory of the Svalbard Archipelago there have been many studies devoted to the content of heavy and trace metals in various environments. Earlier information on the content of metals in soils of the archipelago (Hao et al. 2013; Kłos et al. 2017; Łokas et al. 2019; Ziółek et al. 2017), sediments (Choudhary et al. 2020; Lu et al. 2013), mosses and other components of the biota (Drbal et al. 1992; Grodzinska & Godzik 1991; Kłos et al. 2017; Kozak et al. 2016; Ziółek et al. 2017) was published. However, for cryoconite samples few data are presented, published data on the concentrations of some metals in cryoconite samples from the Midre Lovénbreen Glacier (Singh et al. 2013), Hans glacier (Hornsun) (Łokas et al. 2016), as well as Austre Brøggerbreen and Vestre Brøggerbreen glaciers

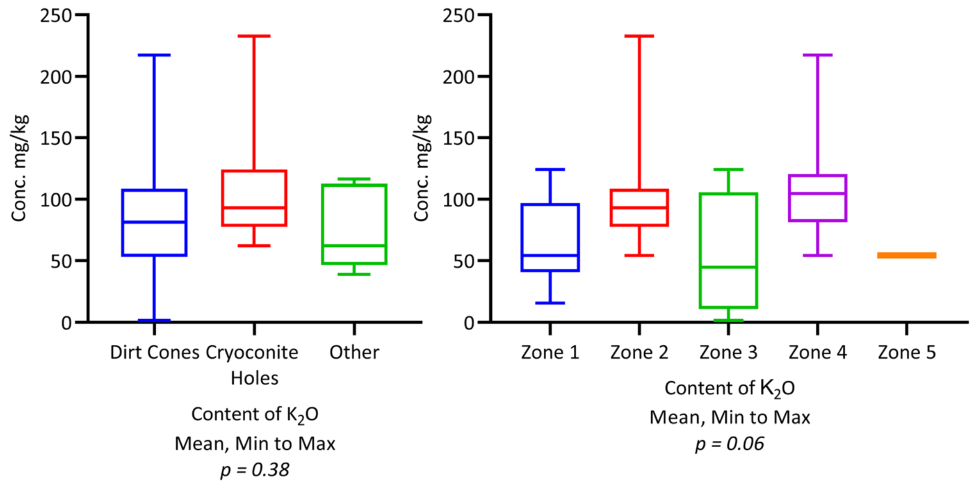

Fig. 13 Mobile potassium content in different forms of accumulation of cryoconite material and sampling areas

Table 1 ANOVA results of the full matrix of data (for standardized data)

Effect	F	p	Observed power (α = 0.05)
Form of accumulation	1.21	0.30	0.66
Sampling zone	***1.58***	***0.03***	***0.99***
Form*Zone	1.26	0.19	0.92

Statistically significant differences are highlighted in bold

(Singh et al. 2017). We obtained new data on the content of heavy and trace metals in the studied zones and various forms of accumulation of cryoconite material (Table 1), as well as constructed maps of the spatial distribution of metal concentrations, which can be seen in the Supplementary Material.

In the table provided in the supplementary materials you can see the variability of concentrations of trace and heavy metals is statistically insignificant both for different forms of accumulation of cryoconite material and for different zones in which this material was sampled (at confidence level $p = 0.05$).

For the complete set of samples (n = 38), the variability in the concentrations of trace and heavy metals is as follows: Cu - 7.1 to 26.9 mg/kg, Pb - 5.1 to 112.8 mg/kg, Zn - 37.6 to 86.7 kg/kg, Ni - 13.3 to 43.8 mg/kg, Cd - 0.27 to 1.34 mg/kg. Maximum Zn concentrations were found in Zone 4 in lake sediments, and the highest Pb concentrations were in the cryoconite hole in Zone 1. Zn maximum was recorded in Zone 2 in the bottom sediments near the glacier edge. For Ni, the maximum concentrations were noted in a sample of cryoconite material from the dirt cone in Zone 4. For Cd, the highest concentrations were observed in a sample of cryoconite from the dirt cone in zone 3.

Previously recorded average concentrations of Zn − 6.33, Cd − 0.420, Cu − 37.67, Pb −54.38 mg/kg in the cryoconite material from the Hans glacier. The authors, analyzing the isotopic ratios of some metals, also came to the conclusion that they have anthropogenic genesis and cryoconite granules concentrate these pollutants (Łokas et al. 2016). On the Austre Brøggerbreen and Vestre Brøggerbreen glaciers, concentrations of Zn 55.7–66.2; Pb 18.5–36.3; Cu 10.7–20.0; Cd 0.01–0.14, Ni 15.7–21.2 mg/kg (Singh et al. 2017). For the Midre Lovénbreen glacier, data on Pb concentrations 49.9–85.1 mg/kg, Cu 39.0–44.0 mg/kg, Zn 132–150 mg/kg, Cd 0.04–0.14 mg/kg were published earlier (Singh et al. 2013). A number of authors also noted that a high level of anthropogenic activity is noted for the Svalbard Archipelago and associated with this quite high concentrations of heavy and trace metals in soils and sediments (Choudhary et al. 2020; Gulinska et al. 2003; Hao et al. 2013; Kłos et al. 2017; Lu et al. 2013). Some researchers estimate that the main source of heavy and trace metals in the high Arctic latitudes is the global mass transfer of fossil fuel combustion products from Russia and Europe (Beine et al. 1996; Macdonald et al. 2005).

Glacial ecosystems are extremely unstable and in constant fluctuations. Cryoconite material is constantly in movement, washed away from the glacier surface into glacial moraines and soils; it can only accumulate in cryoconite holes, dirt cones and various cracks for a long time (Bagshaw et al. 2013; Hodson et al. 2010a; Łokas et al. 2016; Nizamutdinov et al. 2022). Predominantly, the accumulation of particles occurs on flat glacier tops or on not steep glacial slopes, where water flows are not so fast and there is an opportunity for long-term accumulation of cryoconite. However, the age of cryoconite material can be very different, for the Aldegonda glacier previously published data on the large variability in radiocarbon age of cryoconite, from 3675 to 11,120 years (Zazovskaya et al. 2022). The most organic carbon-rich sediments also have a higher content of clay particles and a high adsorption capacity (Abakumov et al. 2022; Langford 2012; Langford et al. 2010). Stable cryoconite material from cryoconite holes is very sensitive to anthropogenic impact, according to some authors cryoconite can act as an object for environmental quality monitoring (Abakumov et al. 2022; Łokas et al. 2019). For example, on the Waldemarbreen glacier (Svalbard Archipelago) increased concentrations of radionuclides of anthropogenic genesis were detected (Łokas et al. 2019). Also for the Garabashi Glacier (Central Caucasus), high concentrations of polycyclic aromatic hydrocarbons of anthropogenic origin were found in cryoconite holes. The authors attribute the increased concentrations of pollutants to the high sorption qualities of cryoconite granules with high content of organic matter (Abakumov et al. 2022; Kushnov et al. 2021). Also, the flushing of cryoconite material from the glacier surface by water streams contributes to the enrichment of glacial moraines and soils with nitrogen and carbon, but also leads to the migration of various pollutants in the "glacier-soil" system (Bagshaw et al. 2013; Cameron et al. 2012; Nizamutdinov et al. 2022; Singh et al. 2013; Telling et al. 2014; Zazovskaya et al. 2022).

In our study, we sampled cryoconite from different forms of accumulation, but no significant statistical differences in the content of pollutants between these forms were found. Statistical analysis using multivariate analysis of variance (MANOVA) for the full matrix of data obtained (pH, clay content, basal respiration rate, TOC and content of trace and heavy metals) was performed at a significance level $\alpha = 0.05$). The results are presented in Table 1.

The factor of the form of accumulation of cryoconite material (cryoconite hole, dirt cones, or other) was found to be insignificant in the complex of parameters studied. The cross-influence of the 2 factors (form and zone) was also not found to be significant.

4 Conclusion

Cryoconite material can accumulate on the surface of the Svalbard Archipelago glaciers in various forms. The thickness of sediments of aeolian genesis affects the formation of glacial relief. Thin layers of material lead to a decrease in albedo and result in the formation of cryoconite holes. When a layer of sufficient thickness accumulates, the cryoconite material acts as an isolating cover and causes the glacier to idle around the thick sediment layer. As a result, piles of cryoconite material with an ice core are formed dirt cones. Cryoconite material is characterized by a granular structure with content of clay fraction less than 12%, independently of the form of accumulation of cryoconite. Emission of CO_2 by microorganisms in some cases more than 100 mg CO_2 per 100 g of material per day and depends significantly on the location of cryoconite sampling. According to the spatial distribution mapping, it was found that cryoconite rich in organic material is located mainly on the glacier tops or on its flat surfaces. Here, meltwater flows are not so fast and the accumulation of organic matter is more active, which is evident from the results of determining the amount of TOC (in some cases, its amount reaches 2.5%, but mainly is in the range of 0.6–1.8%) and available forms of phosphorus (whose concentrations can reach 800 mg/kg). Analysis of the spatial distribution of concentrations of heavy and trace metals showed that the increase in their content may be associated with the amount of organic material in the cryoconite and the features of the washing regime. However, the concentrations of pollutants in cryoconite are not related to the forms of cryoconite accumulation, and the greatest variability is observed between samples taken on different glaciers of the Spitsbergen archipelago. This suggests the presence of uniform arthropogenic pollution of the archipelago or is a consequence of inputs as a result of transboundary transport of pollutants. The mechanism of accumulation and the development of geochemical models of pollutant distribution of high Arctic glacial complexes is the next step in the research and requires a detailed analysis of anthropogenic activity on the archipelago. Statistical processing of the data also did not confirm the relationship between the chemical properties of cryoconite of different forms of accumulation, but significant differences were found between sampling sites, those between different glaciers of the Svalbard archipelago.

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Data Availability The reader can obtain the data of interest on request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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