Analysis of the polydispersity of soil-like bodies in glacier environments by the laser light scattering (diffraction) method

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Abstract

This study presents the results of polydispersity analysis of soil-like bodies from two various polar regions using the laser light scattering method. The differences in the particle size distribution of cryoconite samples from the Anuchin Glacier (Antarctica) and the Mushketov Glacier (Arctic) are described. The samples obtained from the Mushketov Glacier are characterized by a finer particle size distribution than samples collected on the Anuchin Glacier. While comparing our results with previously published studies, it was found that the method of laser light scattering shows a lower content of small fractions (<0.05 mm) compared to the classical methods of sedimentation, since these methods are based on fundamentally different physical principles. The laser method used requires low amounts of samples (0.2–0.5 g), while the classical sedimentary method uses a higher gravimetric portion of cryoconite (5–10 g), which is critical for field sampling.

Keywords: soloids, cryoconites, Anuchin Glacier, Mushketov Glacier

Introduction

The surface of glaciers is never completely clean, and is highly susceptible to spatial and temporal fluctuations (Dumont, Durand, Arnaud and Six, 2012; Petrakov et al., 2019). Glaciers can accumulate on their surface dust particles of various origin, both natural and anthropogenic. The origin of sediments of aeolian or englaciar (Hildes, Clarke, Flowers and Marshall, 2004; Naoko Nagatsuka et al., 2016; Zawierucha et al., 2019) genesis can be revealed by analyzing their chemical, mineralogical and polydisperse composition, as well as by analyzing the meteorological and landscape features of subglacial areas (Glazovskaya, 1952; Ruth, Wagenbach, Steffensen and Bigler, 2003; Lee et al., 2008; Kutuzov et al., 2014).

The polydispersity or particle-size distribution of the solid phase of soils and soil-like bodies (in particular, cryoconites) influences many physical, chemical and biological properties of soils. Polydispersity has a decisive influence on the formation of water–air and thermal regimes of soils and their sorption capacity (Kachinsky, 1958; Kowalski and Andrianova, 1970; Gagarina, 2004; Shein, 2005, 2009; Shein and Madi, 2018).

In current studies, classical sedimentation methods (Kachinsky, 1958; EV. Shein, 2009) to determine polydispersity are increasingly used in conjunction with the more advanced method of laser light scattering (diffraction) (Gee and Or, 2002; Mukhametova, Abakumov and Rumin, 2013; Shein and Madi, 2018).

The use of the laser diffractometry method in the analysis of polydispersity of primitive mineral soils and soil-like bodies of the Arctic and Antarctic is of
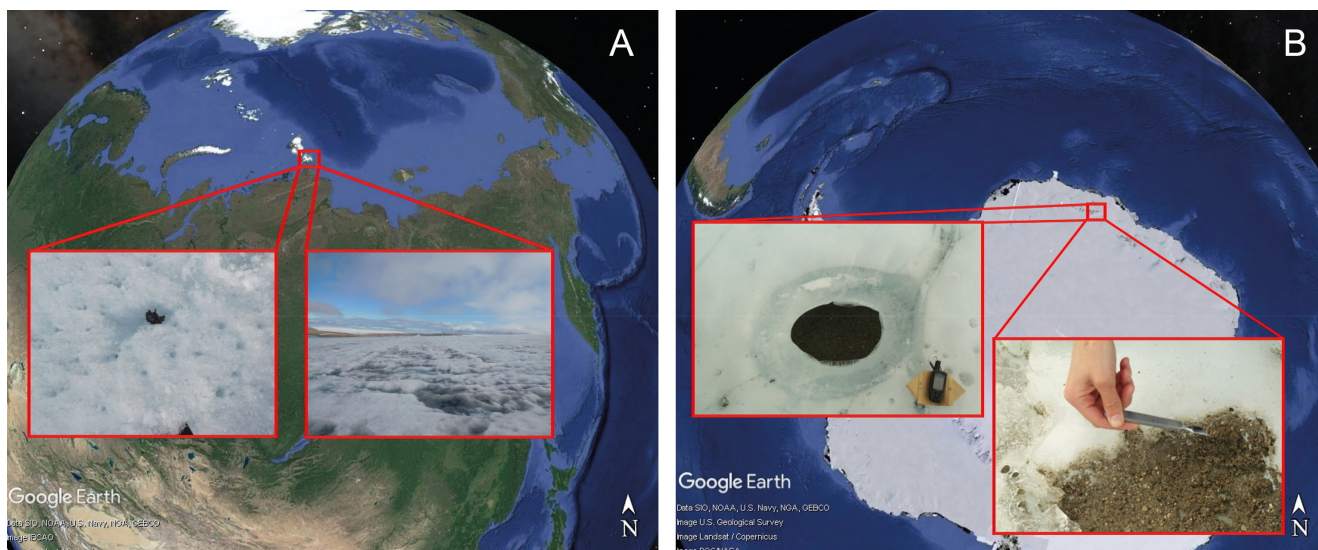
Fig. 1. Cryoconites in sampling area. A — Cryoconite material on Mushketova Glacier (Cape Baranova, Russian Arctic); B — Cryoconite hole founded in Untersee Oasis (Anuchin Glacier, Queen Maud Land, East Antarctida).

particular importance, since the classical sedimentological methods of analysis overestimate the data on silt and finely-dispersed dust content. Correct values of silt and clay content are crucial for understanding the processes of soil formation in polar and high-mountain regions and for understanding the level of absorption capacity of soils and soil-like bodies (Glazovskaya, 1958; Shein, 2005; Abakumov, Pomelov, Krylenkov and Vlasov, 2008; Abakumov, 2010).

On the surface of polar and high-mountain glaciers, ice shelves or sea ice you can frequently find dark-colored clusters of surface dust; these are called cryoconites (Mueller and Pollard, 2004; Nozomu Takeuchi and Li, 2008; Joseph Cook, Edwards, Takeuchi, and Irvine-Fynn, 2016). Cryoconites are sediments of predominantly aeolian genesis; material in cryoconites can also accumulate as a result of landslides of mineral and organic matter from valley walls, and supraglacial and englacial entrainment (MacDonell and Fitzsimons, 2008; Wientjes et al., 2011; Shishkov et al., 2016; Li et al., 2017).

In places of accumulation of dark-colored fine-grained sand, cryoconites form on the glacier surface, which can absorb a much greater amount of solar radiation (Hodson et al., 2008; MacDonell and Fitzsimons, 2008; Cook, Edwards, Takeuchi and Irvine-Fynn, 2016; Abakumov, Gijanski, Chigray and Polyakov, 2020). As a result of the significant difference in albedo between the clear pure glacier surface and the dark-colored cryoconites, active thawing of the glacier body and formation of cryoconite holes (Fig. 1) begin under these dust accumulations (McIntyre, 1984; Wharton Jr, McKay, Simmons Jr and Parker, 1985; MacDonell and Fitzsimons, 2008).

Normally, cryoconite holes do not reach the size of 10 cm vertically and horizontally, but in some cases there are holes even up to 1 meter (Fountain et al., 2004; Mueller and Pollard, 2004; Gajda, 2008).

A cryoconite hole is a water-filled cylindrical depression of tube form with nearly vertical or D-shaped sides (McIntyre, 1984; Wharton Jr, McKay, Simmons Jr and Parker, 1985). Cryoconites consist not only of mineral components (85–95 %), but also of organic matter — they can contain the plant remnants of mosses, algae, bacteria and lichens (Takeuchi, Kohshima and Seko, 2001; Takeuchi, 2002; Cook, Edwards, Takeuchi and Irvine-Fynn, 2016).

The presence of organic matter is responsible for the dark color of cryoconites (Cook, Edwards, Takeuchi, and Irvine-Fynn, 2016). A microclimate is formed in cryoconite holes, which contributes to the growth of primary producers such as cyanobacteria and green algae, which subsequently enrich the cryoconite with biogenic materials (Langford, Hodson, Banwart and Bøggild, 2010; Nagatsuka, Takeuchi, Uetake and Shimada, 2014; Weisleitner et al., 2020). Many authors have noted the rich biodiversity of the microbiome developing in cryoconite holes. Cryoconite holes are a favorable environment for the development of cyanobacteria, Bacteroidetes, Actinobacteria, Proteobacteria and some other bacteria species (Cook et al., 2010; Langford, Hodson, Banwart and Bøggild, 2010; Cameron, Hodson and Osborn, 2012; Cook, Edwards, Takeuchi and Irvine-Fynn, 2016; Weisleitner et al., 2019; Weisleitner et al., 2020). The combination of all these factors makes the organomineral compounds of cryoconites a unique soil-forming structure that remains on the bedrock after the retreat and thawing of the glacier (Singh et al., 2013; Shishkov, Zazovskaya, Mergelov and Dolgikh, 2017; Abakumov, Gijanski, Chigray, and Polyakov, 2020).

Fig. 2. Regional setting and sampling points at the Mushketov Glacier ("Topographic", February 19, 2012).

Cryoconites are of particular interest to study not only in terms of their unique pedogenic, bioaccumulating and organogenic properties. Cryoconite material includes dust from distant continental deserts or agricultural lands, particles from volcanic eruptions or industrial emissions and soot due to its aeolian origin. The analysis of the particle size distribution of soloids (Goryachkin, Mergelov and Targulian, 2019) allows us to establish their genesis in relation to the source of aeolian material (Bizzotto, Villa, Vaj, and Vighi, 2009; Tieber et al., 2009; Mauro et al., 2016). This makes cryoconites a geochemical indicator of transboundary anthropogenic impact on nival-glacial and periglacial areas.

According to other studies, cryoconites are able to accumulate radionuclides of anthropogenic origin (Tieber et al., 2009; Łokas et al., 2018; Usyagina, Ilyin, Meshcheryakov, and Valuyskaya, 2019; Baccolo et al., 2020), potentially toxic elements (Singh et al., 2013; Ferrario et al., 2017; Owens, Blake, and Millward, 2019), polycyclic aromatic hydrocarbons and other synthetic organic compounds (Li et al., 2017; Weiland-Bräuer, Fischer, Schramm, and Schmitz, 2017).

The aim of this work is to compare the polydisperse composition of soil-like bodies of polar regions. To achieve this goal, the following objectives were set: determine the polydisperse composition of cryoconite material using the method of laser diffraction; compare the results with previous studies; identify patterns between the grain-size distribution of soil-like bodies and features of glacial landscapes.

Materials and methods

Polar expeditions have resulted in cryoconite samples collected from the Mushketov Glacier (Bolshevik Island, Severnaya Zemlya Archipelago, 23 km south of the Cape Baranova Arctic Station) and the Anuchin Glacier (Lake Untersee, Queen Maud Land, East Antarctica, 90 km south of the Russian Antarctic station Novolazarevskaya).

Detailed maps of the study areas can be seen in Figures 2 and 3.

The Mushketov Glacier is a glacial dome with an area of about 89 km² and an ice thickness of about
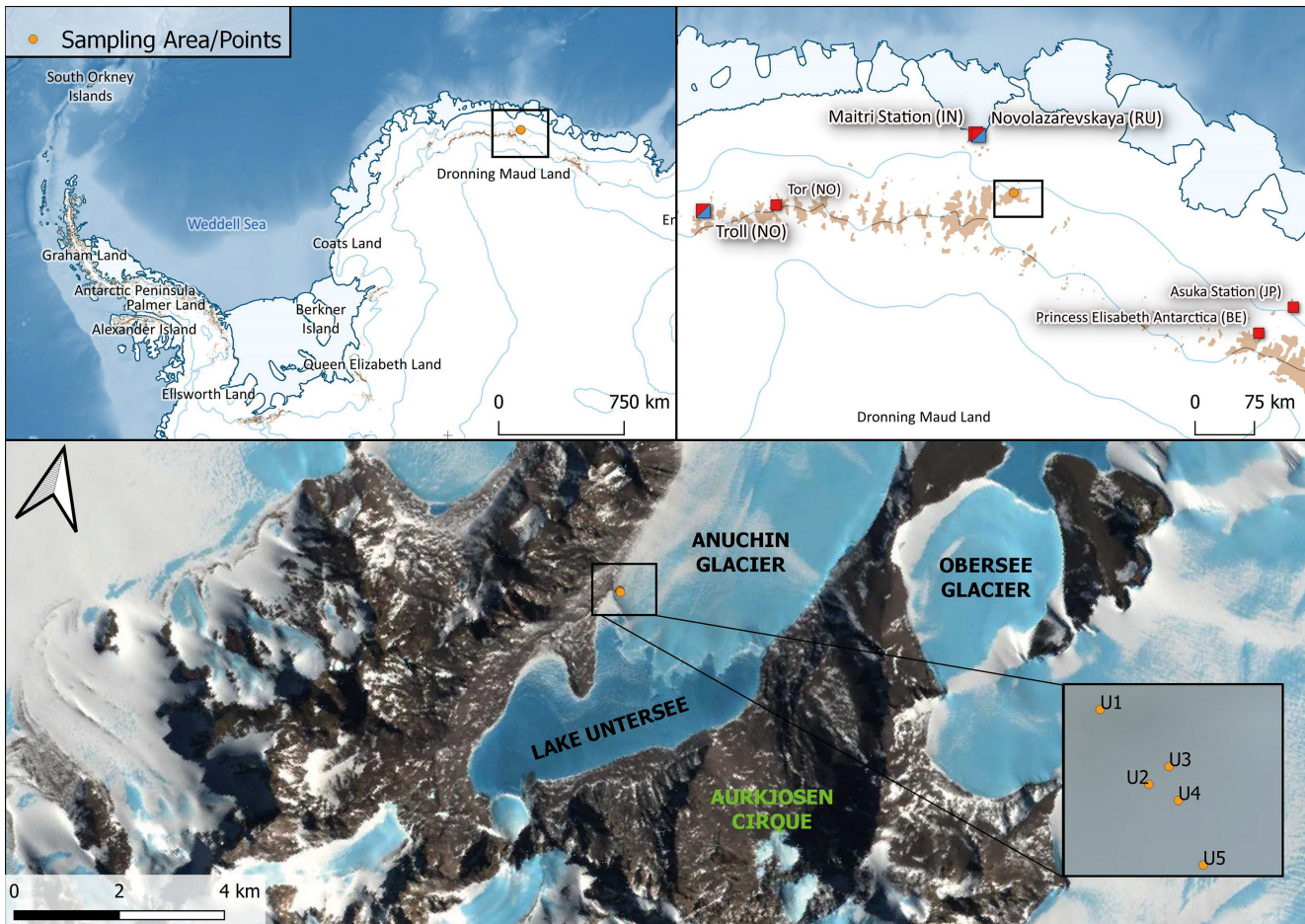
Fig. 3. Study area and sampling points at the Anuchin Glacier (Matsuoka, Skoglund, and Roth, 2018)

160 m, located on the surface of the upper denudation leveling (Bolshiyanov et al., 2016). The island is composed of the Upper Proterozoic terrigenous complex (sandstones, siltstones, granodiorites). Average annual air temperature is –14 °C. The most commonly distributed plants are *Saxifraga cernua, S. hyperborea* and *Stellaria edwardsii*; mosses *Polytrichastrum alpinum* and *Sanionia uncinata;* and lichen *Stereocaulon rivulorum* (Bolshiyanov and Makeev, 1995; Matveyeva, 2006). The area is characterized by stable winds mainly from the southern direction with an average speed of 10–15 m/s (Manousakas et al., 2020).

The Anuchin Glacier is part of the ice cap of Antarctica, the surface of the glacier has southern exposure, and the surface area of the glacier is 34 km². The coverage of cryoconite holes on the Anuchin Glacier is 3.5 % (1.2 km²) on average, with highest density observed near the glacier-lake interface in the southwestern part of the glacier (Weisleitner et al., 2019). The glacial surface has a pronounced cell-polygonal character. Southerly winds prevail, with an average daily maximum of 15 m/s (Levitan et al., 2011; Weisleitner et

al., 2019). No regular vegetation was found close to the sampling points.

After collection, the samples were air dried and transported to the laboratory of the Department of Applied Ecology of SPBU for further analysis. Before the analysis, the field samples were put through a sieve with a diameter of 2 mm, and weighed. The polydispersity of soil-like bodies was analyzed by the laser light scattering (diffraction) method according to the Russian method "GPM 1.2.1.0008.15 Determination of particle size distribution by laser light diffraction" with repeated measurements for each sample (GPM, 2016).

The method is based on the principle that particles of a given size diffract light at a certain angle that increases with decreasing particle size. This method allows detection of particles the size from 0.1 μm to 2000 μm (Gee and Or, 2002; Domkin, 2011; Uspenskaya, Syroeshkin, Pleteneva and Dobrovolsky, 2016). The laser diffraction method is more effective for measuring sand and silt fractions compared to sedimentation methods for analyzing the particle-size distribution of soils (Shein, 2009; Shein and Madi, 2018).

Samples were placed in 10 ml of 4% $Na_4P_2O_7$ solution for peptization of colloids before analysis, followed by grinding.

The processed sample was separated on a sieve with a diameter of 0.25 mm. Particles remaining on the sieve were washed into a bowl and dried to a constant weight at 105 °C, after which they were weighed on an analytical scale. The mass of the sample was found from the difference of masses, and the percentage of 1–0.25 mm fraction was calculated.

Fraction distribution in the range of 0.03–250 μm was determined on a Shimadzu SALD-2201 (Japan) device. Blank measurement was carried out with distilled water. The refractive index of 3.0–0.2i was used to process the results. Measurement on the diffractometer was carried out in at least threefold repeats.

Statistical data processing and visualization of the results were performed using Statsoft Statistica v12.5, TriQuick, and QGIS 3.16.

Results and discussions

In some studies cryoconites classify as a specific type of soil — soloids or soil-like bodies (Targulian, Mergelov and Goryachkin, 2017; Goryachkin, Mergelov and Targulian, 2019). This assumption allows us to consider cryoconites as Lithic skeletal and mineral soils and to use all the fundamental principles of classical soil science to study them.

As previously mentioned, cryoconites can be geochemical indicators of transboundary anthropogenic impact on nival-glacial and periglacial areas. The particle-size distribution, specific surface area of soil colloids, and microaggregate composition play an important function in the sorption capacity of soils (EV Shein, 2005), including the accumulation of pollutants in soils and soloids. It is known that a significant part of trace elements is accumulated in the fine-graded (<0.005 mm) fraction due to the high absorption capacity of the clay fraction (Kowalski and Andrianova, 1970; Gagarina, 2004).

Results of polydispersity analysis

The results of the polydispersity analysis of cryoconites are shown in Table 1, with classification into fractional classes according to Kachinsky (1937). We can see that cryoconites from two different study areas have a different particle-size distribution.

Samples from the Anuchin Glacier (East Antarctica) are characterized by sandy composition. In all selected cryoconite samples, the content of sand fractions dominates. The minimum content of average sand was in sample U3 — 76.31 %; the maximum in U5 — 97.12 %. The content of fine sand in the samples varies from 1.84 % in U5 to 15.35 % in U3. The percentage of finer fractions (medium and fine dust) in all samples is less than one percent, except for U3, which had 1.21 % medium dust and 2.10 % small silt. The percentage of large silt in all samples is <5 %. The content of clay particles in all samples was <1 %.

Cryoconites from the Mushketov Glacier (Russian Arctic) are more finely dispersed compared to samples from the Anuchin Glacier. In the particle-size distribution, there is a large fraction of fine sands and coarse dust. The small sand content varies from 42.95 % in B2 to 54.05 % in B6. The minimum content of large silt was found in sample B6 — 20.80 %; the maximum in the sample B3 — 49.19 %. The percentage of medium sand fraction was <15 %. The maximum fraction of medium sand was found in samples B1, B3, and B6 at 11.71, 14.56, and 15.88 %, respectively. Medium and small silt

Table 1. Contents of particle size classes, % (± 95 % Confidence Interval) (Kachinsky 1937)

|		Medium sand (>0.25 mm)	Fine sand (0.25–0.05 mm)	Large silt (0.05–0.01 mm)	Medium silt (0.01–0.005 mm)	Fine silt (0.005–0.001 mm)	Clay (<0.001 mm)
Anuchin Glacier	U1	88.94±0.11	7.87±0.20	2.29±0.10	0.35±0.03	0.44±0.05	0.12±0.05
	U2	85.17±0.28	10.31±0.38	2.91±0.33	0.63±0.08	0.87±0.15	0.11±0.10
	U3	76.31±0.21	15.35±0.46	4.46±0.61	1.21±0.05	2.10±0.08	0.57±0.11
	U4	94.52±0.07	3.80±0.06	1.15±0.04	0.23±0.01	0.25±0.01	0.06±0.03
	U5	97.12±0.03	1.84±0.03	0.70±0.02	0.14±0.00	0.17±0.01	0.03±0.01
Mushketov Glacier	B1	11.71±1.62	50.78±0.83	25.62±1.07	5.46±0.27	5.30±0.31	1.12±0.90
	B2	2.46±0.84	42.95±1.15	39.49±1.23	7.75±0.32	5.92±0.29	1.43±1.42
	B3	14.56±2.90	49.19±2.68	24.20±0.66	5.89±0.03	5.80±0.32	0.36±0.44
	B4	5.04±1.07	52.35±2.86	29.99±1.51	6.36±0.55	5.66±0.67	0.60±0.26
	B5	2.77±0.37	47.87±2.04	34.00±1.23	7.48±0.40	6.77±0.54	1.11±1.07
	B6	15.88±1.65	54.05±1.58	20.80±0.19	4.30±0.07	4.43±0.20	0.54±0.24
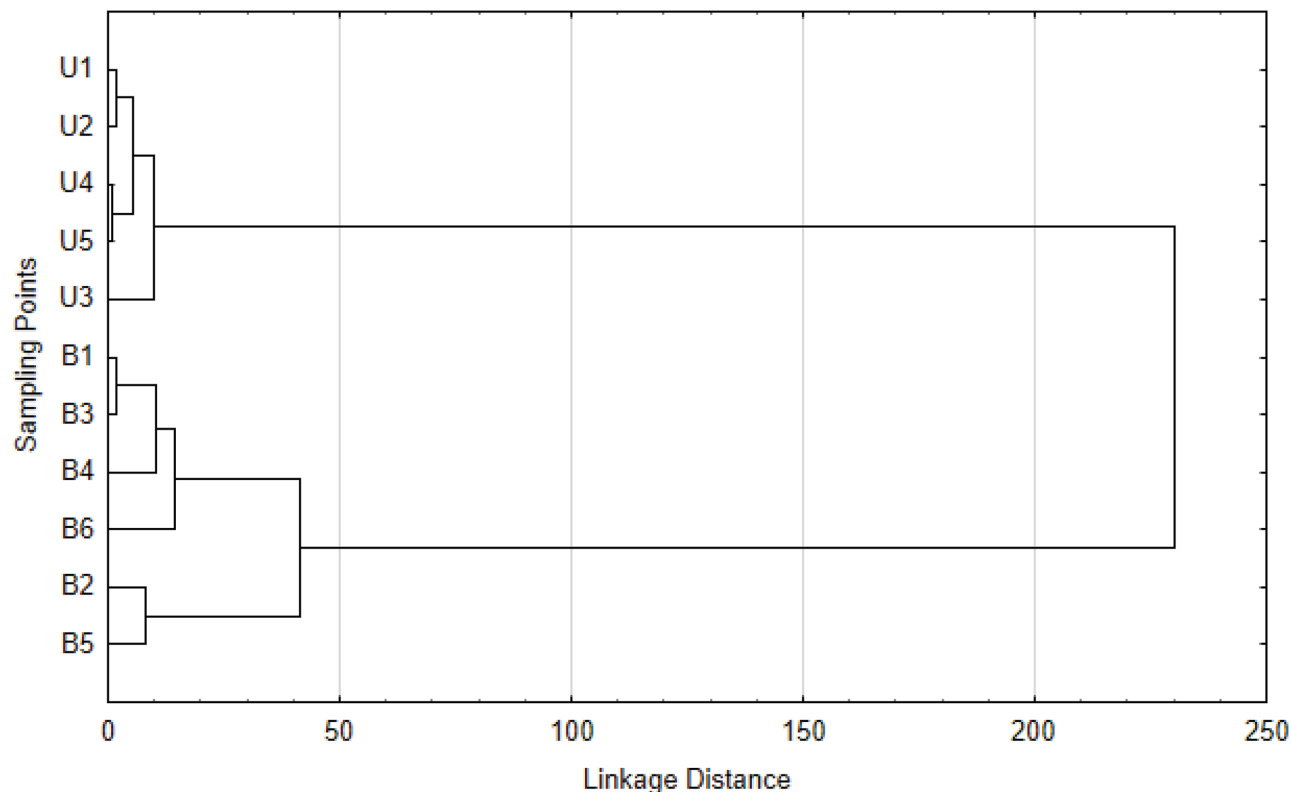
Fig. 4. Cluster Tree Diagram for 11 samples of cryoconites from cape Baranov (B1–6) and Untersee oasis (U1–5). For cluster analysis we used Ward's method with Euclidean distance metrics.

content in all samples was <8 %. The percentage of the clay fraction ranges from 0.36 % in B3 to 1.43 % in B2.

Cluster analysis of the obtained data using the (Ward, 1963) method with the Euclidean metric statistically confirmed the difference in the particle-size distribution in the two study areas. As you can see in the diagram in Figure 4, the data were divided into two clusters. One cluster — points U1–U5, contains all samples obtained from the Anuchin Glacier (East Antarctica). The second cluster — points B1–B6, contains all samples obtained from the Mushketov Glacier (Russian Arctic).

To understand which textural classes the studied cryoconite samples relate to, a ternary plot of particle sizes (Figs. 5 and 6) was constructed for each study area. Classification of texture classes was performed according to the triangular diagram (Jahn et al., 2006). To construct the plots, the total percentages of sand, % (medium sand + fine sand), silt, % (large + medium + fine silt) and clay, % were pre-calculated.

As can be seen in the ternary plot (Fig. 3), the material from the cryoconite holes collected at the Anuchin glacier can be classified as sand. A more detailed consideration shows that the content of clay particles for all samples (except for U3) is <1 %. The content of sand fraction varies from 91 % in U3 to 99 % in U5.

The samples collected from the Mushketov Glacier are very different from the material from the Anuchin Glacier. The cryoconite material from the Mushketov Glacier is finer. According to the textural class (Fig. 4), samples B1, B3, B4, and B6 belong to Sandy Loam; B2 and B5 — to Loam (WRB, 2015).

The highest variability is in the sand and silt fractions. The sand fraction varies from 45 % in B2 to 70 % in B6. The variability of the silt fraction ranged from 25 to 47 % for samples B6 and B2, respectively.

Discussions

Cryoconites have an important role in the formation and regulation of the current climatic situation. The accumulation rate and quantity of cryoconite material on the surface of glaciers is directly related to their degradation (Wharton Jr, McKay, Simmons Jr and Parker, 1985; Podgorny and Grenfell, 1996; Fountain et al., 2004) and the intensity of aeolian processes (Glazovskaya, 1952). Since the accumulation of matter in cryoconite holes is mainly related to aeolian processes, it is important to understand the primary nature of the origin of the particles that accumulate on the glacier surface. Cryoconite material can play the role of a geo-
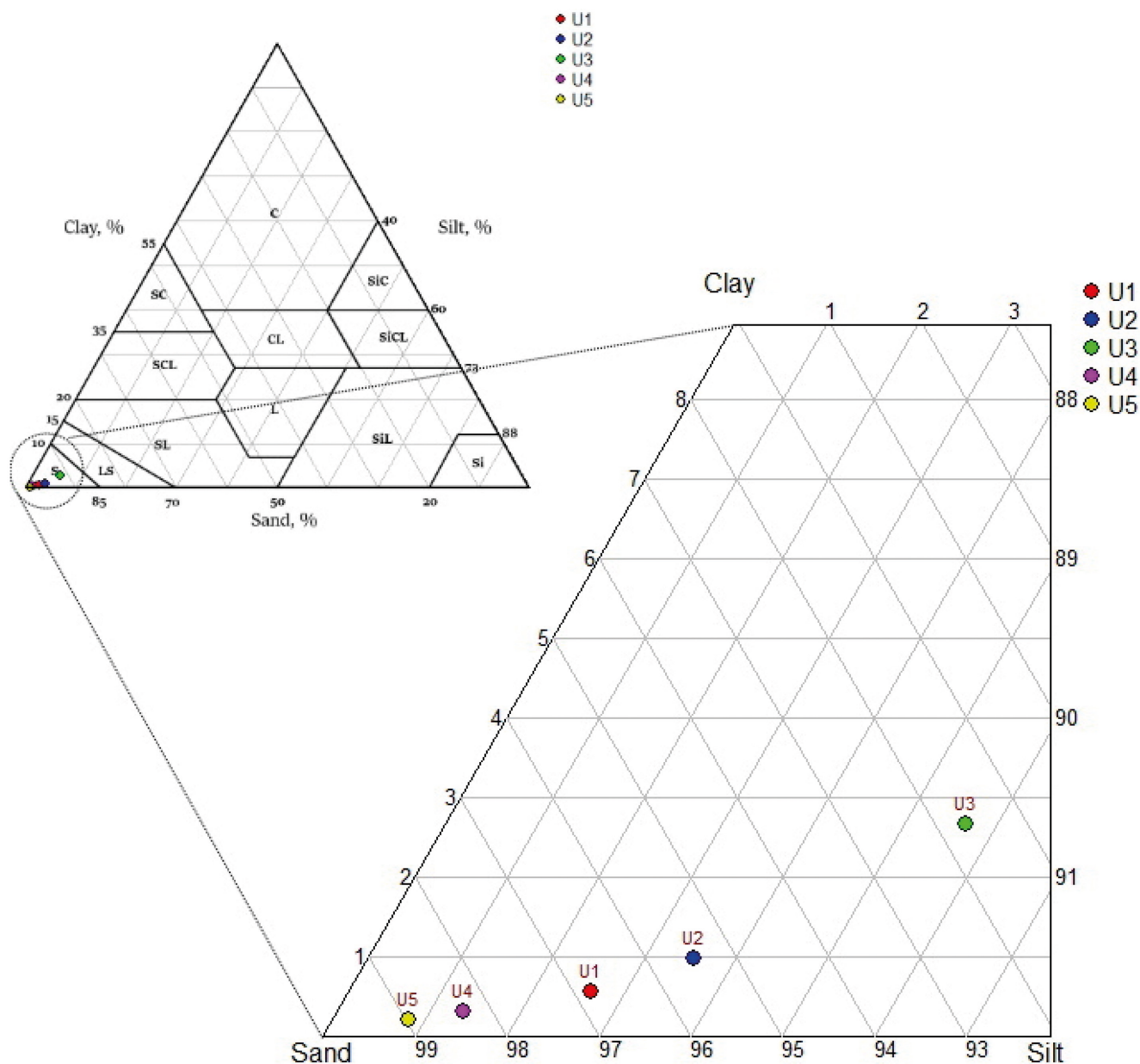
Fig. 5. Ternary plot of particle sizes for cryoconite samples from Anuchin Glacier (fractional content, %).

chemical indicator of anthropogenic impact on glacial areas. By understanding the nature of the origin of the cryoconite material, it is possible to assess the degree of influence of the anthropogenic factor on the melting of glaciers. In this context, it is important to obtain reliable data on the particle-size distribution of sediments of aeolian genesis (Glazovskaya, 1952). The setting of traps on the glacier surfaces will assist to collect and sample migratory material of various origin (dust, fluvial grains). Since black carbon particles of anthropogenic origin (which are emitted by incomplete combustion of coal, wood, and fossil fuels (Goldberg, 1985; Masiello, 2004; Ramanathan and Carmichael, 2008; Baccolo et al., 2020) accumulate predominantly in clay

particles (Glazovskaya, 1958; Ukalska-Jaruga, Smreczak and Klimkowicz-Pawlas, 2019), the quantitative evaluation of grain size distribution becomes quite important for glacier surface retreat rate.

As mentioned earlier, the use of classical sedimentation methods to estimate the particle-size distribution often overestimates the percentage of fine fractions in comparison with the results obtained by laser diffractometry (Abakumov, Pomelov, Krylenkov and Vlasov, 2008; Shein, 2009; Shein and Madi, 2018).

Some researchers have already studied the particle-size distribution of cryoconite and moraine aggregates around Lake Untersee and the Anuchin Glacier (Levitan et al., 2011; Weisleitner et al., 2019; Weisleitner
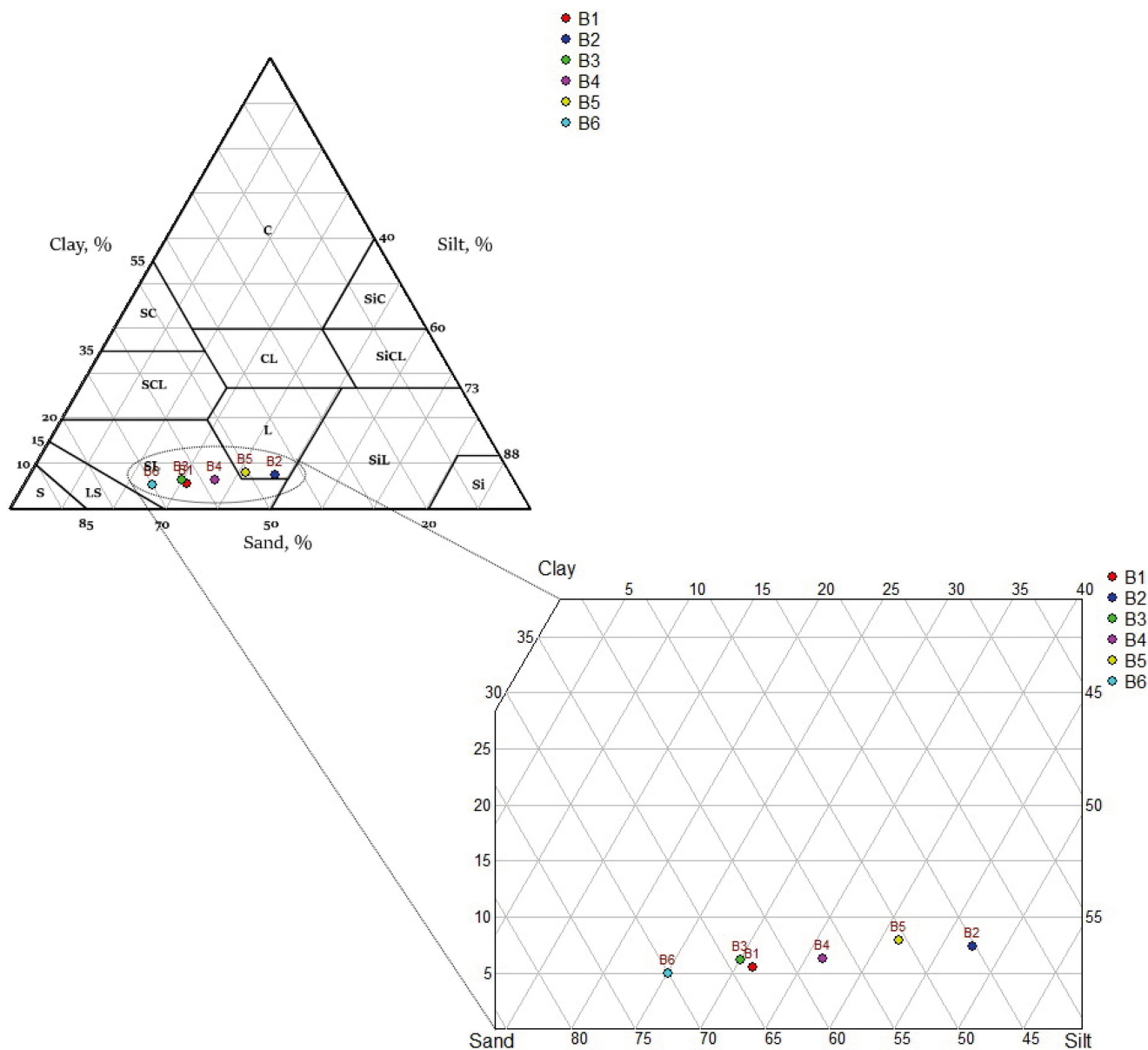
Fig. 6. Ternary plot of particle sizes for cryoconite samples from Mushketov Glacier (fractional content, %).

et al., 2020). For the Mushketov Glacier area, it appears that we performed this analysis for the first time.

Weisleitner et al. (2020) used the wet sieving method. It should be noted that their study area is very close to our sampling sites. They investigated samples of material from cryoconite holes on the Anuchin Glacier in the Anuchin North of Ridge (ANR) and on the glacier along the medial moraine (AMH, AML). Levitan et al. (2011) researched the particle-size distribution of moraine deposits and "dirty ice" in the vicinity of Lake Untersee and the Anuchin Glacier using the classical sedimentation (water-mechanical) method. We made a comparison of our results with the results published earlier (Levitan et al., 2011; Weisleitner et al., 2020; Weisleitner et al., 2020); a comparative diagram can be seen in Figure 7.

The results obtained during our research differ significantly from the results of previously published investigations. The use of laser diffractometry showed a lower percentage of fine fractions (<0.01 mm). Mostly the percentage fraction <0.01 mm is less than 2 %. The results of other studies significantly varied, up to 4.5 % with the wet sieving method (Weisleitner et al., 2020) and up to 12.3 % with the classical sedimentation method (Levitan et al., 2011).

Conclusions

The variations in the polydisperse composition of cryoconites can be associated with differences in the conditions of cryoconite hole formation and the in-
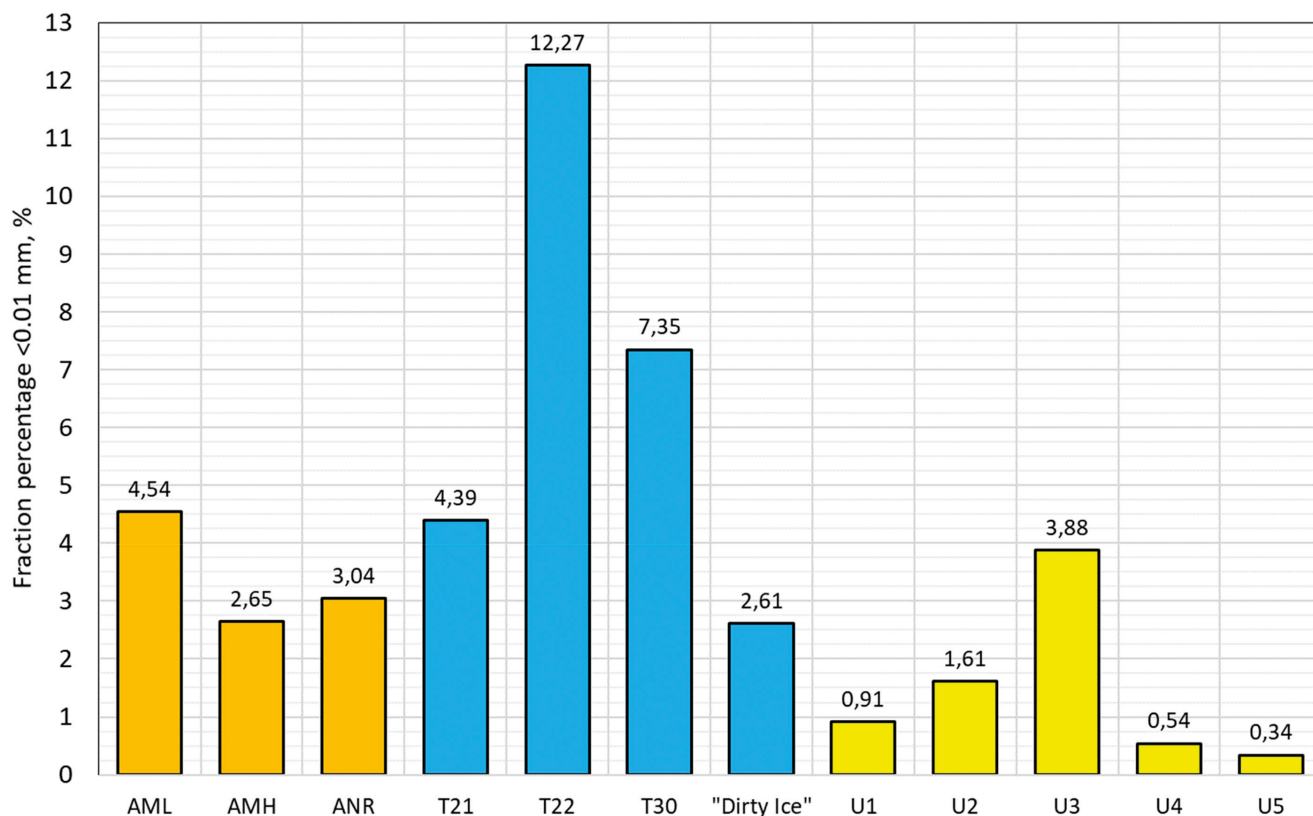
Fig. 7. Percentage of the fine fractions <0.01 mm, %. T21, T22, T30, "Dirty Ice" (Levitan et al., 2011), WIP, AML, AMH, ANR (Weisleitner et al., 2019).

fluence of local landscapes on aeolian sedimentation processes. The Anuchin Glacier and Lake Untersee are surrounded by the Gruber Mountains, which may limit aeolian mass transfer processes. The cryoconite material in the cryoconite holes on the Anuchin Glacier is characterized by a dominance of heavy fractions (medium sand, >0.25 mm). Accumulation of material occurs mainly as a result of landslides from glacier valley walls.

The mass transfer of fine fractions is not limited. Cryoconite holes on the Mushketov Glacier may be much more active in accumulating material of aeolian or englacial genesis. Probably, the accumulation of particles on the glacier has been taking place for a long time. The specific location of Bolshevik Island makes it highly affected by the transport of particles as a result of the polar circulation of air masses. Wind currents, as a result of the polar circulation, can bring in fine particles both from the mainland and from the more northern islands of the Severnaya Zemlya archipelago. Silt and clay fractions can be transported from the mainland or neighboring islands and easily deposited on the glacier surface and accumulate in the cryoconite holes. Therefore, the polydisperse composition of cryoconite material from the Mushketov Glacier is dominated by small sand and silt fractions (0.25–0.01 mm).

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SOIL BIOLOGY