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Micromorphology of cryoconite on Garabashi and Skhelda glaciers and soils of Baksan Gorge, Mt. Elbrus, Central Caucasus

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Abstract: In the Central Caucasus region, the intense process of deglaciation is identified as caused by cryoconite formation and accumulation. The fine earth materials were collected on the surfaces of Skhelda and Garabashi glaciers as well as from zonal soils of Baksan Gorge and were studied in terms of chemical, particle-size, and micromorphological features. Supraglacial sediments are located at the glacial drift area of material and, thus, due to transfer of these sediments to the foothill area, their fine earth material can affect micromorphological and chemical characteristics of adjacent zonal soils. Thin sections of mineral and organo-mineral micromonoliths were analyzed by classic micromorphological methods. Data obtained showed that the weathering rates of cryoconite and soil minerals are different. The cryoconite material on the debris-covered Skhelda Glacier originated from local massive crystalline rocks and moraines, while for Garabashi Glacier the volcanic origin of cryoconite is more typical. Soils of Baksan Gorge are characterized by more developed microfabric and porous media, but their mineralogical composition is essentially inherited from sediments of glacial and periglacial soils. These new data could be useful for understanding the process of evolution of the mineral matrix of cryoconite to the soil matrix formed at the foot of the mountain.

Keywords: Russia, Caucasus, sediments, weathering, deglaciation.

Introduction

Glacier degradation is an ongoing process in the Arctic, Antarctic, and mountain environments (Nosenko *et al.* 2013; Kotlyakov *et al.* 2017). Frequency of mudflows and other hazardous mountain events increased in the Central Caucasus in the last 20 years, which is associated with retreating of glaciers (Aleinikova *et al.* 2020). This may cause mechanical instability and engineering safety risks for buildings and structures (Marchenko *et al.* 2017). Current researches address mainly glacier mass balance (Nosenko *et al.* 2013), rate of the glacier movement (Kotlyakov *et al.* 2017), and formation of cryoconite fractures and holes as a factor of formation of mudflows in mountain areas (Aleynikova 2008; Marchenko *et al.* 2017). Nowadays, cryoconite is considered as an important sediment in a rapidly changing glacial and supraglacial environment due to its ability to decline albedo of the glacier surface (Takeuchi 2002), high microbial activity (Anesio *et al.* 2009) and micromorphological features (Kalińska *et al.* 2021), which can influence adjacent territories.

The term 'cryoconite' comes from the Greek language meaning "cold dust" and it was first used by Nordenskjöld in Greenland (Nordenskjöld 1875). It usually refers to discrete, aggregate granules of mineral and organic matter, located within the supraglacial zone, often in "cryoconite holes" (Cook *et al.* 2016). Inorganic matter in cryoconite consists mostly of mineral fragments, mainly phyllosilicate, tectosilicate and quartz as a substrate for bacterial community (Stibal *et al.* 2008; Langford *et al.* 2010). Organic matter consists of plant and animal residues as well as of living and dead microorganisms (Takeuchi *et al.* 2010; Wientjes *et al.* 2011). Cryoconite formation is a result of mineral grains deposition on the glacier surface by aeolian, fluvial, mass-movement and melt-out processes (Hodson *et al.* 2008).

Cryoconite holes are reservoirs of nutrients with their ongoing biochemical cycle that leads to the accumulation and transformation of nutrients (Bagshaw *et al.* 2013). It was noted that cryoconite contains 2 to 7 times higher nutrients than the initial soils. Under conditions of deglaciation, material from cryoconite holes can be transferred to temporary water flows, which are the most productive systems in Antarctica (Fountain *et al*. 1999). Substances, derived from cryoconite could be considered as a source of nutrients for ecosystems with deficit of biogenic and mineral elements (Gooseff *et al.* 2004; Bagshaw *et al.* 2007, 2013; Ball *et al.* 2011). Nutrient flow is closely related to granulometric and micromorphological features of sediments and soils, since the particle size affects the cation exchange capacity (Bagshaw *et al.* 2013; Lokas *et al.* 2016; Fortner and Lyons 2018). On the other hand, cryoconite are considered as a reservoir of microorganisms on the glacier with ongoing photosynthesis (Takeuchi 2002; Hodson *et al.* 2008). Accumulation of organo-mineral materials and its transformation by microorganism leads to formation of specific humic substances (Takeuchi *et al.* 2001; Takeuchi 2002; Pengerund *et al.* 2017; Polyakov *et al.* 2019).

A previous study of cryoconite micromorphology from the Caucasus region shows the occurrence of silt-sized fraction greyish minerals with the dominance of smooth edges grains transformed by chemical weathering (Zawierucha *et al.* 2019). It was found that local geomorphology and geology features are more important than the regional climate in shaping the mineral grains. Other important factors, which could influence the mineral grains shape, especially quartz, are chemical processes in biological systems such as photosynthesis, which depends on the rate of microbiological activity (Kalińska-Nartiša *et al.* 2017).

Data obtained in this study can be useful in order to estimate the hypothetical drift area of the accumulated material in the zone of ongoing deglaciation in the Central Caucasus. In this context, our goal is to analyze the physicochemical parameters and micromorphological composition of sediments in cryoconite holes. The aim is also to assess the degree of transformation of the cryoconite material. These new data, in comparison with study of local soils micromorphology, may be useful in order to better understand the transformation of the mineral matrix of cryoconite and its role in the formation of primary soils after glacial retreat.

Study area

The study area is located in the Elbrus region, Kabardino-Balkarian republic, Russia. The average air temperature in the Elbrus region in summer (June–August) is 11.6°C. The amount of precipitation (September–May) is 655 mm. Mt. Elbrus was an active volcano during three periods, *i.e.*, 225 000–170 000, 110 000–70 000 and less than 30 000 years ago (Gurbanov *et al.* 2004).

The Elbrus glacier complex is the largest glacier in the Caucasus. In total, there are 23 glaciers descending from mountain ridges. Their total area is approximately 120 km^2. The study site is represented by two glaciers in the Mt. Elbrus valley in Central Caucasus Mountains: Garabashi and Skhelda (Fig. 1). Garabashi Glacier is a part of the southern slope of the glacial massif of Mt. Elbrus, the fifth highest volcano in the world (5642 m). The glacier begins at about 4900 m and terminates at 3330 m. Its area in the 1980s and 1990s was 4.47 km^2. Garabashi Glacier feeds the Baksan River basin. Since 1982, the glacier lost 14% of its volume and 11.4% of its area. Skhelda Glacier is located southeast of Mt. Elbrus. There are moraines on the surface of glacier tongues. The thickness of the moraine cover varies from 50 to 200 cm, which sharply decreases the glacier melting rate. Garabashi Glacier is an open glacier and Skhelda Glacier is debris-covered glacier. Local soils as well as mudflow were sampled at Baksan Gorge close to the Mt. Elbrus (Fig. 1).

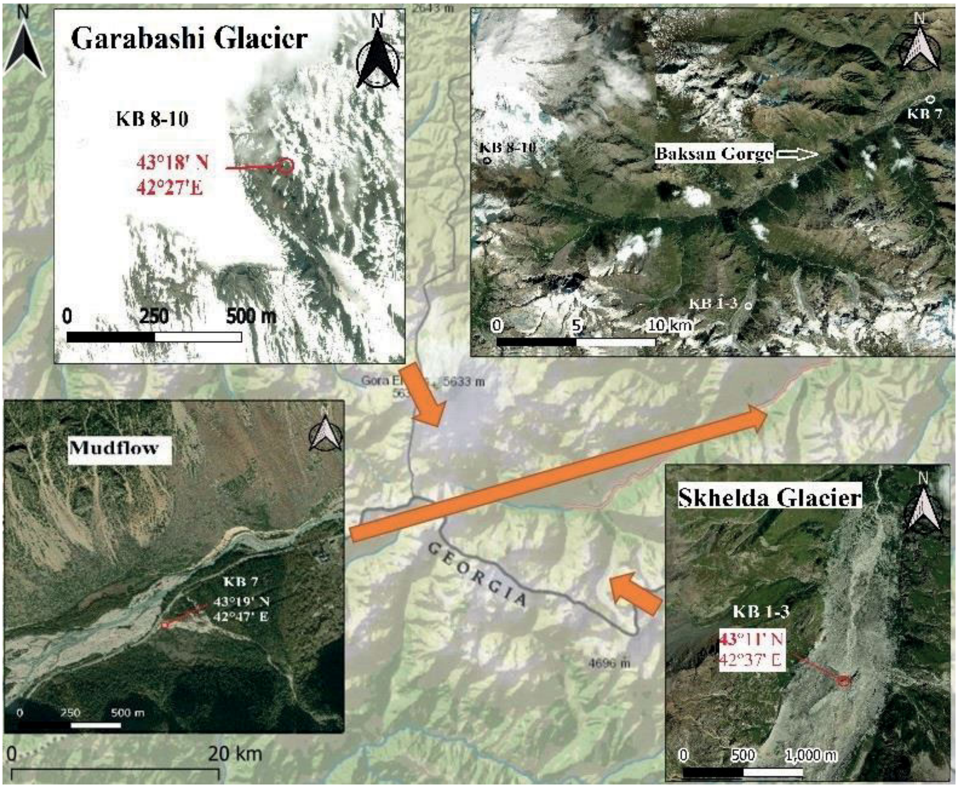

Fig. 1. Location of cryoconite and mudflow sampling plots. Detailed map on a larger scale is in the top right corner. Satellite images from Esri Satellite Map (QGIS3 program).

Materials and Methods

Sampling strategy. — The description and characterization of the studied samples are presented in Table 1. On Skhelda Glacier, samples were taken from the slopes of the debris-covered glacier. Friable sediments of various genesis cover the lower slope of the glacier that is in motion due to the deglaciation. At Garabashi Glacier, samples were taken from the glacier fractures as well as from terminal moraine (Fig. 2).

Soil samples were taken at different locations of Baksan Gorge to survey the nature of cryoconite and to compare features of cryoconite materials, sampled in two different glaciers. The formation of soils in mountainous and foothill areas is associated with the periglacial accumulation of transported material from high altitudes. We investigated sediments that were transferred there by mudflows in 2019. These sediments are currently subject to transformation and soil-forming. There is already some vegetation. The mudflow sediments can be presented as an evolutionary model that represents the transformation of cryoconite sediments during the present soil formation.

Table 1

Sampling points for studying cryoconite, soils and mudflow sediments.

Study site	Sample ID	Description	Coordinates (N E)	Altitude (m a.s.l.)	Material	Sampling date
Skhelda Glacier	KB 1	material from the slope of the glacier	43°11’27” 42°38’45”	2385	cryoconite	15.09. 2020
	KB 2	cryoconite derived material				
	KB 3	material from the slope of the glacier				
The right bank of the Baksan river to the village Neutrino	KB 4	Entisol (Chestnut soils) from the north slope of the Baksan river bank	43° 17’21.0” 42° 42’57.9”	1617	soil	16.09. 2020
The left bank of the Baksan river to the village of Upper Balkaria	KB 5	Entisol (Chestnut soils) from the south slope of the Baksan river bank	43° 19’44.0” 42° 48’08.8”	1466		
Elbrus region, the surroundings of Kendelen village	KB 6	Chernozems from Kiendelen village	43° 35’21.7” 43° 13’40.1”	750		
Mudflow area	KB 7c	mudflow occurred in 2019	43° 19’19.2” 42° 47’15.1”	1490	soil-like body, derived from mudflow with vegetation	
	KB 7b				soil-like body, derived from mudflow without vegetation	
Garabashi Glacier	KB 8	cryoconite from the ice fracture on Garabashi Glacier	43°18’18” 42°27’49”	3860	cryoconite	17.09. 2020
	KB 9	cryoconite over ice				
	KB 10	moraine sediments on the glacier				

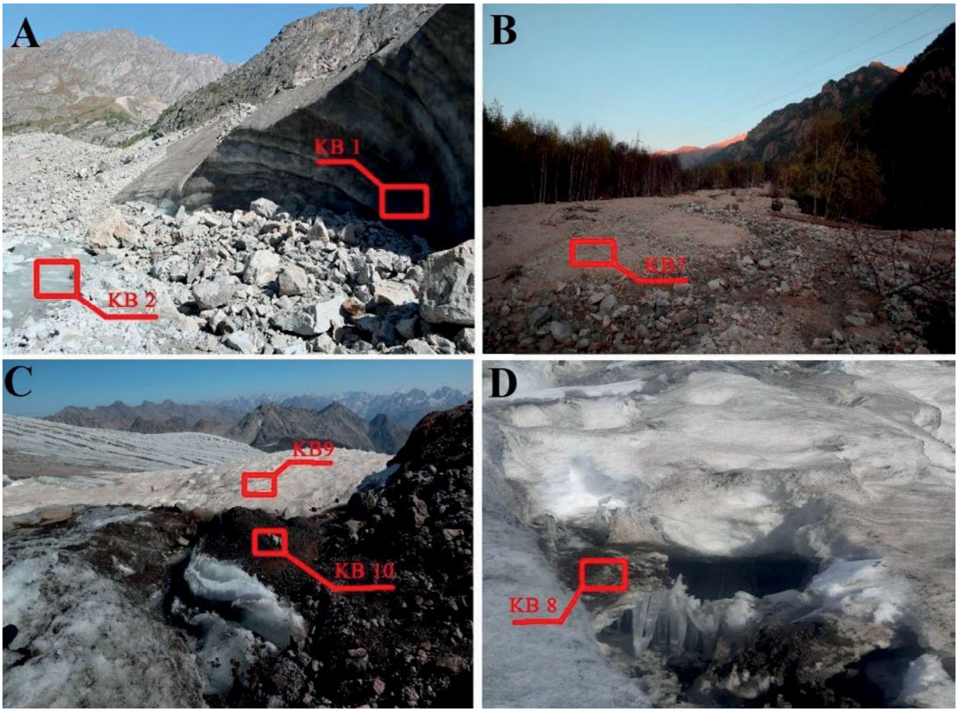

Fig. 2. Sampling locations on the surface of Skhelda (**A**), mudflow (**B**) and Garabashi (**C** and **D**) glaciers. Photographs by E. Abakumov.

Laboratory studies. — All chemical soil parameters were analyzed in fine fraction of soil, after sieving through a 2 mm mesh. The soil organic carbon (SOC) content was determined by the dichromate oxidation–titration method (Walkely 1947). pH was measured in water and $CaCl_2$ suspension (1:2.5). The particle-size distribution of soils was determined by "wet sedimentation" or the Kachinsky method, a Russian analog of the analysis proposed by Bowman and Hutka (2002). The basal respiration was determined in laboratory incubation experiment in chambers (Jenkinson and Powlson 1976) in order to estimate the microbiological activity in studied materials, which is related to transformation of transferred easily accessible organic matter.

Thin sections (20x20x1 mm) of soil material were prepared from micro monoliths of the soil samples. Thin sections were investigated with the Leica DM750P polarization microscope (Leica Camera AG, Wetzlar, Germany), in transmitted light and crossed nicol prisms. The following soil micromorphological indexes were investigated: soil microfabric, spatial arrangements of fabric units, soil particle distribution and their geometrical features, elements of microstructure, and the nature of organic matter. The terminology used in this paper is published by Stoops (2003), Gagarina (2004) and Gerasimova *et al.* (2011). Details of the micro organization of soil were described and categorized after Stoops and Eswaran (1986) and Stoops (2003, 2009).

Statistical analysis. — For statistical processing of the data, the PAST (Paleontological Statistics) software has been used. We conducted a pairwise comparison of studied physicochemical parameters (pH, SOC, basal respiration, particle-size distribution) using ANOVA in order to confirm or refute the hypothesis about the difference in physical and chemical features of cryoconite on different glaciers.

Results

Sample chemistry. — The samples investigated show nearly neutral, *i.e.*, weakly acidic to weakly alkaline, reaction. Predominantly, the reaction was neutral (Table 2). The SOC is high in the studied soils (up to 2.86%), according to the parametrization by Orlov (1985). On the other hand, in the samples of mudflow sediments and in the cryoconite, the SOC is rather low (max. 0.29%). The exception is sample KB8 with SOC reaching 1.41% of SOC. This sample shows a slightly acidic reaction (pH = 5.84). As a result of the organic matter accumulation, the basal respiration parameter in the sample from the surface of Garabashi Glacier (KB8) is on average 2.5 times higher than on Skhelda Glacier. The mudflow sample shows low SOC value (0.28%) and low basal respiration values (11 mgCO_2/100g per day) in comparison with studied soils. According to one-way ANOVA, significant difference is observed only between the values of basal respiration ($F = 7.72$, $p = 0.049$, Degr. of Freedom = 1).

Particle-size distribution. — The particle-size distribution in the studied sediments shows that cryoconite is dominated by sand particles (particles diameter 0.05–1 mm), its content in most samples ranges from 65.8% to 89.37%. The content of clay particles (particle diameter <0.002 mm) is low in almost all the samples. It does not exceed 7.32%. Among all the samples, cryoconite KB8 stands out. Its clay fraction content is 14.1%, showing the highest value among all the samples, and the sand content is 29.71%, showing the lowest value. The silt fraction (particles diameter 0.001–0.05 mm) predominates in KB8 with the content of 56.19%. According to WRB (2015), sample KB8 can be categorized as silt loam. KB9 sample has the highest sand fraction content among all samples (89.37%) and the lowest silt content (3.31%), which makes it possible to categorize it as sand. Other samples of cryoconite can be categorized as sandy loam or loamy sand (Table 3).

The sand fraction prevails in the soil samples. Its content varies between 75.30% and 85.12%. It also shows the largest difference between the particle size distributions in the soil samples and cryoconite. The majority of cryoconite samples are dominated by coarse and medium sand (particles diameter 0.25–1 mm). Its content varies from 52.92% to 68.28%. In the soil samples, the content of coarse and medium sand does not exceed 35.41%. In all the soil samples, the fraction of fine sand (particles diameter 0.005–0.25 mm) dominates. Its content ranges from

Table 2.

Physicochemical properties of the cryoconite, soils and mudflow sediments.

Sample	Horizons*	pH (H_2O)	pH ($CaCl_2$)	SOC (%)	Basal respiration ($mgCO_2$/100g per day)	Skeletal fraction (%)	Fine earth (%)
KB 1	surface of the glacier	6.07	5.17	0.16	24.2	93.40	6.60
KB 2	cryoconite derived material	6.54	6.35	0.28	11	14.90	85.10
KB 3	surface of the glacier	6.45	5.96	0.11	6.6	44.00	56.00
KB 4	Oe	6.49	5.67	2.86	39.6	49.50	50.50
	Ah	6.58	5.60	1.61	39.6	65.60	34.40
	A/C	6.44	5.61	0.89	17.6	43.60	56.40
KB 5	Ah	6.90	6.05	2.44	48.4	16.10	83.90
	A/C	6.98	6.06	2.15	30.8	21.10	78.90
	Ck	6.98	6.30	1.37	17.6	38.10	61.90
KB 6	Ah	7.89	-	2.49	22	44.30	55.70
	Bk	7.82	-	0.68	26.4	31.20	68.80
KB 7	Ch	7.24	-	0.15	17.6	31.00	69.00
	C	6.95	6.92	0.13	17.6	32.20	67.80
KB 8	surface of the glacier	5.84	4.45	1.41	41.8	12.60	87.40
KB 9	cryoconite over ice	7.25	-	0.29	24.2	84.60	15.40
KB 10	C	6.16	5.49	0.05	39.6	46.20	53.80
Minimum				0.05	6.6	12.6	6.6
Maximum				2.86	48.4	93.4	87.4
Standard deviation				0.99	12.19	23.31	23.31
Coefficient of variation				92.78	45.95	55.81	40.04

* according to FAO (2006)

42.97% to 60.89%, while in the cryoconite samples this value does not exceed 48.60%, averaging 20.80%. The amount of clay particles in the soil samples is higher than that in the cryoconite samples. It varies from 6.97% to 12.39%. All the studied soil samples can be categorized as sandy loam or loamy sand.

Moreover, differences between cryoconite and the soils are observed in the silt fraction content. On average, it is higher in the cryoconite samples than in the

Table 3

Particle size distribution and texture classes of the studied soils, cryoconite and mudflow sediments.

Sample	Horizon*	Coarse and medium sand (0.25–1 mm)	Fine sand (0.05–0.25 mm)	Coarse silt (0.01–0.05 mm)	Medium silt (0.005–0.01 mm)	Fine silt (0.001–0.005 mm)	Clay (< 0.001 mm)	Texture class
KB 1	surface of the glacier	64.53	4.55	25.36	1.88	0.36	3.32	sandy loam
KB 2	cryoconite derived material	67.55	8.21	21.81	2.04	0.11	0.28	loamy sand
KB 3	surface of the glacier	63.98	1.82	21.44	6.64	1.36	4.76	sandy loam
KB 4	Oe	29.55	42.97	11.2	2.64	2.20	11.44	sandy loam
KB 5	Ah	24.01	56.98	8.08	1.52	0.84	8.57	loamy sand
	A/C	23.42	58.02	9.56	2.36	1.44	5.20	loamy sand
	Ck	35.41	49.71	0.38	2.94	6.56	5.90	sandy loam
KB 6	Ah	20.03	60.89	8.96	2.24	1.60	6.28	loamy sand
	Bk	24.07	51.23	7.08	3.04	12.4	2.28	loamy sand
KB 7	Ch	56.73	25.12	10.35	1.04	2.16	4.60	silt loam
	C	52.92	39.64	2.56	0.48	0.96	3.44	sand
KB 8	surface of the glacier	12.28	17.43	14.97	40.70	0.89	13.72	loamy sand
KB 9	cryoconite over ice	68.28	21.09	2.96	0.24	0.12	7.31	sandy loam
KB 10	C	35.42	48.60	8.56	4.68	0.56	1.88	loamy sand
Minimum		12.28	1.82	0.38	0.24	0.11	0.28	
Maximum		68.28	60.89	25.36	40.7	12.4	13.7	
Standard deviation		20.11	21.08	7.50	10.35	3.33	3.69	
Coefficient of variation		48.71	60.69	68.58	200.16	147.90	65.44	

* according to FAO (2006)

soil samples, amounting to 22.12% and 11.50%, respectively. In KB 8 cryoconite sample, there is an evident dominance of the medium silt (particles diameter 0.005–0.01 mm). Its content reaches 40.70%, meanwhile the content of coarse silt and fine silt is 15.86%. In KB 1 cryoconite sample, the content of coarse silt (particles diameter 0.01–0.05 mm) is 25.36%, while the total content of medium silt and fine silt is 2.24%. In the studied soil samples, maximum difference of silt fractions with different particle diameters does not exceed 10%, which is not as essential as in cryoconite samples. At the same time, there is a tendency to increase the content of the silt fraction with a smaller particle diameter as we move deeper into the soil profile. According to one-way ANOVA, significant difference is observed in the content of coarse silt ($F = 14.49$, $p = 0.02$, Degr. of Freedom = 1).

Micromorphological features. — Micromorphological characteristics of the studied soils, cryoconite and mudflows in thin sections are presented in Figs. 3–6. Figure 3 shows the soil fabric from the cryoconite hole of Skhelda Glacier. The material is weakly transformed and has an angular blocky microstructure. There are no organic remains and, in general, the aggregates do not show the biogenic origin. The low degree of transformation of mineral particles is associated with

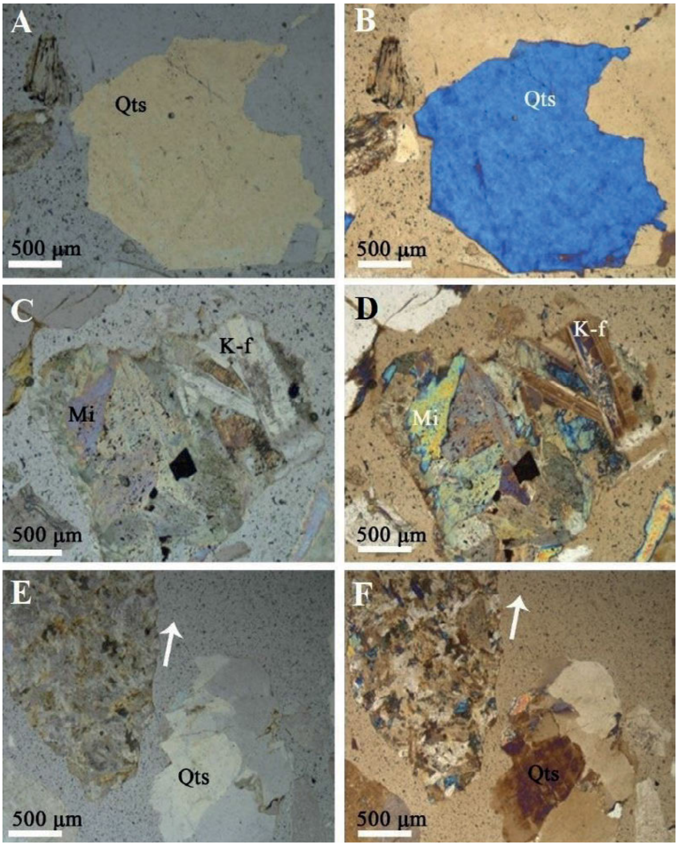

Fig. 3. Micro fabric of cryoconite from Skhelda Glacier (KB 1): **B**, **D** and **F** in plane-polarized light; **A**, **C** and **E** in crossed polarized light. Qts – quarts; Mi – mica; K-f – K – fieldspar; vertical orientation of the mineral (arrow).

low rates of biogeochemical processes in cryoconite holes (Table 2). The main mechanism for the transformation of minerals is the mechanical weathering of particles. As to the mineral composition of quartz grains, sand-silt aggregates prevail including mica and feldspar. The microstructure of aggregates from another sample of Skhelda Glacier cryoconite (KB2) is also angular blocky, which indicates low alteration and similarity to the rock materials. The orientation of the minerals is poorly expressed or not expressed at all. The vertical orientation of minerals arises in the course of various processes occurring in soils, noting the development of cryoconite in Skhelda Glacier. In general, orientation is associated with the processes of sorting material (soil, rock) and the lack of orientation is associated with the absence of active processes of transformation of mineral particles. Therefore, in the conditions of cryoconite from Skhelda Glacier, we can note the accumulation of weakly transformed material.

Mineral grains are mica (muscovite or/and biotite), feldspar and quartz. There are also no visible organic remains. The main source of mineral particles on this glacier are rocks. The accumulation of organic matter in cryoconites occurs under the influence of the aeolian factor.

Figure 4 shows thin sections of the alluvium and mudflow materials of Skhelda Glacier. They show only a few signs of transformation: the angular

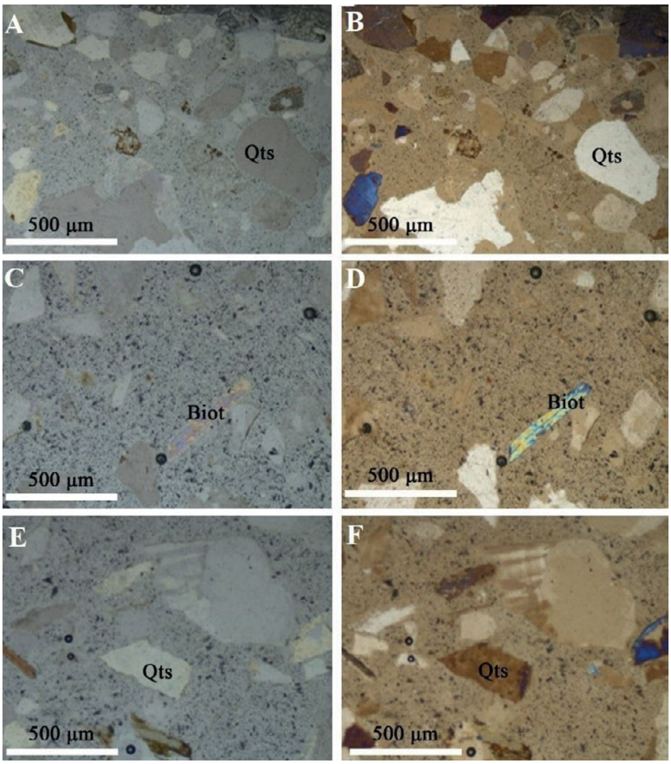

Fig. 4. Micro fabric of the thin sections of KB 2 (**A** and **B**) and KB 7 (**C**–**F**). Images B, D and F are in plane-polarized light; A, C and E in crossed polarized light. Qts – quarts; Biot – biotite.

blocky microstructure and low degree of weathering in alluvium (A and B) and the mudflow sediments (C–F). The alluvium and mudflow samples have high roundness rate of the samples. The soil fabric has a random size distribution. This is due to the seasonal movement of water flows and movement of the mineral particles. The mineral composition is represented by quartz in the alluvial material with weak signs of ferruginization. The low degree of ferruginization is associated with a minor change in the redox conditions of these sediments. The mudflow sediment includes feldspar without signs of serritization, angular blocky of quartz and single inclusions of mica. There are also weak signs of ferruginization. In general, both samples have similar features, *i.e.* the random distribution of the material, affected by the mechanical transformation of mineral materials. There is a large porous space between the minerals.

Figure 5 shows the thin section of soil from Mt. Elbrus. Soil fabric is represented by biogenic sand-clay aggregates. The composition includes organic matter, mica and feldspar. Organic matter is represented by organic fine material. There are fractures on the mineral grains associated with the biological type of weathering. The development of vegetation cover, an increase in microbiological activity and the accumulation of soil organic material indicate active processes of biological transformation of the material.

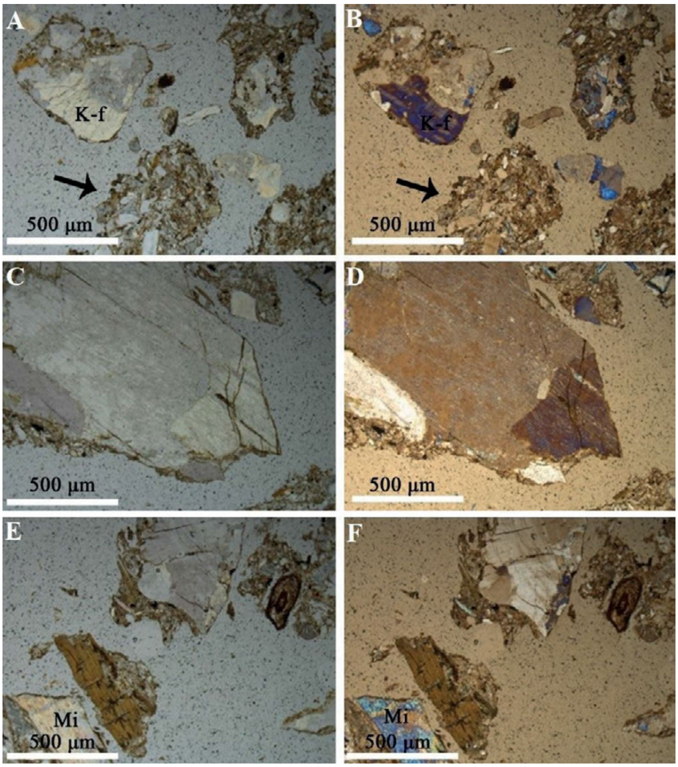

Fig. 5. Micro fabric of the thin section of Entisol (KB 4): **B**, **D** and **F** are in plane-polarized light; **A**, **C** and **E** in crossed polarized light. K-f means K-fieldspar; Mi – mica; biogenic sand-clay aggregates are arrowed.

Figure 6 shows a few examples of the thin sections of cryoconite, taken from the fractures in Garabashi Glacier. The mineral composition is dominated by quartz and pyroclastic material. Accumulation of the latter is associated with the eruption of the Elbrus volcano. The last eruption was dated at < 30 000 years ago (Gurbanov *et al.* 2020). At relatively low temperatures, this material was practically not affected by weathering processes. The pyroclastic material contains mica and quartz grains. Aggregates are not expressed, which is associated with a weak transformation of the material. Plasma consists of a clay fraction, which is formed during the mechanical destruction of rocks. Figure 6 (C and D) shows plate quartz with parallel cracking occurring when the initial material is mechanically destroyed.

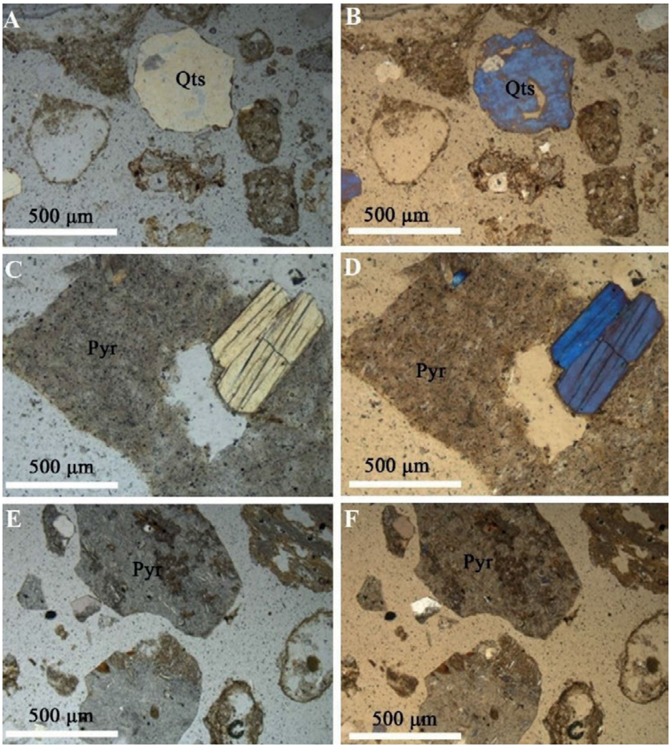

Fig. 6. Thin section of cryoconite from Garabashi Glacier (KB 8 and KB 9): **B**, **D** and **F** are in plane-polarized light; **A**, **C** and **E** in crossed polarized light. Qts-quarts; Pyr-pyroclastic.

The fabric elements of Garabashi Glacier moraine have a random orientation, enaulic double spaced related distribution, angular blocky microstructure. Organic matter is represented by organic fine material. The transformation type is an isomorphous alteration with a cross-linear alteration pattern. There are signs of iron formation. The mineral composition is represented by feldspar without any signs of seritization.

Discussion

Sample chemistry. — According to obtained data (Table 2), there is a variability in the pH, in the soils of mountainous regions (KB 4 and KB 5), a neutral reaction takes place. In zonal soils, the reaction is alkaline (KB 6). Much higher values of SOC in soils are associated with a high degree of humification of organic matter in the soils of the Baksan Gorge and the development of organo-mineral soil horizons. Sample KB 8 from Garabashi Glacier shows high values of SOC (1.41%), basal respiration (41.8 mgCO_2/100g per day) and acidic reaction, which may indicate the accumulation of fresh organic residues in the cryoconite hole, that is delivered with precipitation, subsequent humification and formation of specific organic acids. Based on basal respiration values, the most intensive metabolism is typical for the soil horizons, as well as for cryoconite from Garabashi Glacier (KB 8 and KB 10) due to allochthonous input of fresh organic matter. Relatively low SOC (0.15%) and basal respiration values (17.6 mgCO_2/100g per day) in mudflow sediments are observed due to fact that those sediments are populated by plant communities relatively slowly. The plant residues are the main source of SOC (Franzluebbers 2005). An essential amount of SOC accumulates in the soils of the foothills (up to 2.86%). Within the soil profile, there is a tendency towards a decrease in the content of SOC with depth. Such a distribution is typical for the southern bioclimatic zone.

The formation of specific communities along meltwater streams is associated with the presence of gravimetric moisture, but the soil is also enriched with nutrients that are transferred from high-altitude areas along with cryoconite sediments (Foreman *et al.* 2007). The relevant task in the study of cryoconite is their ability to act as a substrate for microbial and plant communities (Anesio *et al.* 2009; Antony *et al.* 2011; Amato *et al.* 2017; Sanyal *et al.* 2018; Weisleitner *et al.* 2020). Redistribution of organomineral matter during deglaciation contributes to the material accumulation in the periglacial zone and the involvement of these sediments in modern soil formation (Bagshaw *et al.* 2007, 2013). Cryoconite sediments enriched in nutrients are involved in the ongoing soil formation, thereby forming stable local ecosystems in the foothill areas. Soils in foothill areas are annually enriched with nutrients dissolved in water, and they can be even more productive than zonal soil analogs (Glazovskaya 2005b).

From the data obtained, we can note that in the soils of the foothill areas (KB 4 and KG 5), the SOC is higher than in the zonal soils (KB 6), which is also noted with the indicator of microbiological activity. Apparently, the influence of temporary water flows, which originate from cryoconite, has a positive effect on the accumulation of organic matter and the development of microbial communities in foothill areas. Thus, we confirm that the soils formed in the foothill areas are more productive than the zonal variants of soil formation.

Particle-size distribution. — Mountain systems, such as the Caucasus, the Alps, the Tien Shan, and others, are where the accumulation and redistribution of organomineral sediments occur. Some of these sediments accumulate on the surface of glaciers and are involved in the formation of a network of cryoconite. From the obtained data (Table 3), the cryoconite-derived fine particles from Skhelda and Garabashi glaciers are carried over to adjacent biological ecosystems since in the mountainous areas of Elbrus intense snowmelt occurs in the summer. Fluvioglacial material is normally transported along with meltwater flows, thus mineral and organic-mineral compounds enter mountain and foothill ecosystems (Solomina *et al.* 1994).

The reduced size of particles in the studied soil samples as compared to the cryoconite samples results from soil weathering. It was previously noted that weathering processes in mountain regions are influenced by vegetation due to production of organic ligands (Egli *et al.* 2008), which intensify weathering, as well as by microorganisms through changing pH, production of helating ligands and organic acids (Castaldini *et al.* 2002). Weathering rates decline rapidly with increasing altitude due to dependence of biological activity on the temperature and precipitation regime (Riebe *et al.* 2004). In our study, the degree of transformation is less pronounced in cryoconite compared to the soils. In the samples from the mudflow, a content of >50% coarse and medium sand was found, while the accumulation of finer particles may be due to the mechanical destruction of the mineral component of the soil as the material was carried by water from the mountain down to its foot (Glazovskaya 2005a). With the input of rock material into the soil, a significant chemical and physical changes occur, as reflected by the micromorphological structure of soils (Kubiëna 1970; Konistsev and Rogov 1977; Mazurek *et al.* 2016).

Micromorphological features. — Cryoconite sediments from different glaciers differ between themselves and in respect to soils in terms of micromorphological features. Cryoconite material on Skhelda Glacier (Figs. 3 and 4) can be generalized as weakly weathered sediment of recent origin. The weathering is of the physical type in low humidity (low content of Fe-Mg noodles) and low content of organic remains. Mineralogicaly, samples from Garabashi Glacier (Fig. 6) are different from Skhelda Glacier cryoconite.

In the studied cryoconite, ferruginization of mineral particles is not observed, which is common in well-aerated conditions. An increase in ferruginous particles is observed in waterlogged conditions (Rogov and Konistsev 2008). The accumulation of clay fraction in the soil plasma indicates the processes of mechanical destruction of the primary material (Rogov and Konistsev 2008; Świtoniak *et al.* 2016; Maksimova and Abakumov 2017). The low iron content in cryoconite is usually associated with deep-aeration of the material, as well as mechanical destruction of rock material (Kubiëna 1938; Kaczorek and Sommer 2003). The synchronization of sedimentation processes, biopedogenic alteration and transformation of moraine and aeolian sediments lead to the formation of subaerial sedimentary soils. Their development is associated with the transformation of organomineral material and its burial under fresh moraine material (Glazovskaya 2005a). In the course of mudflows and seasonal water streams originating in the upper parts of the mountain systems, organomineral particles are transferred to the foothills (Solomina *et al.* 1994).

According to the data obtained, organic matter accumulates in cryoconite from Garabashi Glacier as a result of the aeolian mechanism of matter accumulation. At the same time, mineral particles have weak signs of transformation, similarly as on Skhelda Glacier. Thus, we can conclude that in cryoconite the accumulation of material occurs predominantly with minor further development. The soils of the periglacial zone are quite different from the material that accumulates in cryoconite in terms of their structure. In the studied soils, aggregation of mineral particles and weathering (mostly biological) of primary minerals, such as feldspar, mica, take place. On the other hand, mineralogical composition of soils and cryoconite is similar and consists mostly of quartz and mica in both studied materials. Therefore, transfer of mineral particles from cryoconite affects the mineralogical composition of the studied soils at the foothill, the main difference is the degree of development and its structure.

Conclusions

This micromorphological study has shown that the cryoconite of the Central Caucasus makes a significant contribution to the soils of periglacial landscapes and mountain areas. It was shown that accumulation and transformation of organic matter cause a more pronounced degree of alteration of the mineral part in zonal soils. A weak transformation of mineral particles and low organic matter content were observed in cryoconite materials. Mechanical alteration of rocks leads to the formation of sandy and clayey plasma. This process is more pronounced in soils of the gorge, while it is on initial stage in cryoconite materials. The studied microfabric of the cryoconite materials is characterized by random orientation, enaulic single- and double-spaced distribution. The microstructure of all studied cryoconite thin sections is angular blocky due to the physical destruction. The mineral composition of cryoconite mineral mass inherited from the moraines, superficial glacier sediments and products of massive crystallic rocks weathering. The cryoconite materials of Garabashi Glacier is formed mainly by pyroclastic material of the Mt. Elbrus. These structural features of the micromorphological composition indicate the "freshness" of the sediment mineral composition and a low degree of transformation during the formation of cryoconite holes. Soils of the Baksan Gorge are characterized by more developed microfabric and porous media, but their mineralogical composition is essentially inherited from sediments of glacial and periglacial soils.

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